Microwave Metamaterial Antennas and Other Applications

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Abstract

Metamaterials have attracted great attentions due to their ability to control electromagnetic waves and the unusual properties. This presentation will be focused on the application of metamaterials in microwave antennas and other devices, exploring better performance and/or new features. Three types of metamaterial antennas are presented: zero-index material antennas, small patch antennas for wireless communications, and metamaterial lens antennas.

We propose and experimentally demonstrate two kinds of anisotropic zero-index materials (AZIMs) in the Cartesian and cylindrical coordinates, respectively. The Cartesian AZIMs (such as *z* component of permittivity or permeability tensor equals zero) are shown to generate perfectly plane waves in the *z* direction, resulting in high-directivity antennas. We make two-dimensional (2D) and three-dimensional (3D) experiments to verify such new features. On the contrary, the radially AZIMs (radial component of permittivity or permeability tensor in the cylindrical coordinate equals zero) will always produce omnidirectional radiations regardless the numbers and positions of sources inside AZIM. We also show experimentally the powerful ability of AZIM to reach high-efficiency spatial power combination for the omnidirectional radiations.

Abstract

We experimentally demonstrate efficient methods to improve the bandwidth and radiation efficiency of patch antennas and reduce the coupling among patch antenna array using metamaterials, which are important to the wireless communications (e.g., MIMO systems).

We present two kinds of metamaterial lens antennas. First, we demonstrate a series of 3D broadband, low loss, dual polarization, and high-directivity planar lens antennas which are realized using gradient-index metamaterials, which have excellent features and superior performance than traditional antennas (horns or Rotman lenses). Second, we propose and realize a 3D Luneburg lens with flattened focal surface using the transformation optics. The novel 3D lens has great advantages to the conventional uniform-material lens and spherical Luneburg lens with no aberration, zero focal distance, a flattened focal surface, and the ability to form images at extremely large angles. It can be directly used as a high-gain antenna to radiate or receive narrow beams in large scanning angles for dual polarizations.

Finally, we present some other applications of metamaterials, including the polarization converters, perfect absorbers of electromagnetic waves, and random-refractive-index metasurfaces to reduce the radar cross sections.

Keywords: Microwave Metamaterial Antennas, Applications.

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Contents

- Background and Motivation
- Small Metamaterial Antennas
- Anisotropic Zero-Index Material Antennas
- Metamaterial Lens Antennas
- Other applications
- Summary

Background: Antennas

What do we concern on a practical antenna?

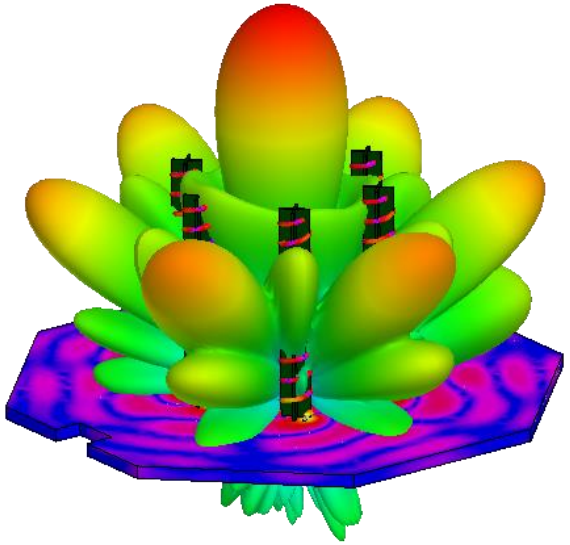
Two factors:

- **Geometrical & mechanical factor**
- **Electrical factor**

- **Size, Weight**
- **Shape (2D, 3D, Array, etc.)**
- **Power Capability**

Antenna Parameters

Electrical Parameters



- Gain, Directivity,
- Bandwidth
- Reflection Coefficient, Efficiency
- Beam width, Sidelobes
- Beam Forming, Beam Steering
- Polarization, Coupling

Limit and Constraint

Similar to the diffraction limit in imaging, there is a Gain Limit in Antennas:

$$G_{\max} = \frac{4\pi A}{\lambda^2}$$

There are also constraints between:

- **Gain and Bandwidth;**
- **Gain and Sidelobe;**
- **Beam Steering Angle and Bandwith;**
- **……**

Motivation

The Role of Metamaterials in Antennas:

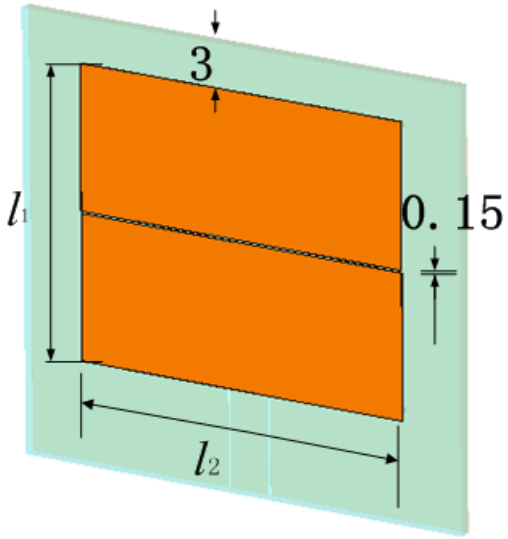
- How to improve the performance of antennas?
- How to use metamaterials to build up new-concept or new-type antennas?
- Can we break the constraints of antennas?
- Can we break the limit of antennas?

Small Metamaterial Antennas

- Resonance: Reduce the size;
- Artificial Magnetic Substrate: Increase efficiency and bandwidth;
- Reduce mutual coupling of antenna array.

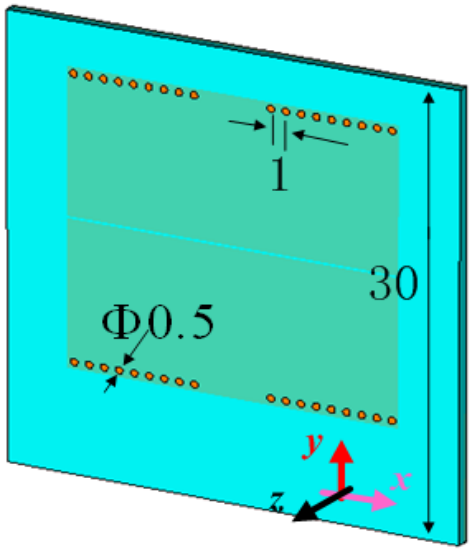
Applications: Wireless Communications, etc.

Small Resonant Antennas



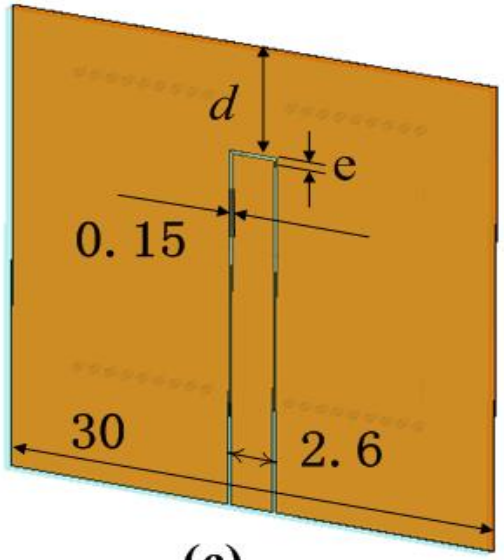
(a)

Top Surface: Two Radiation Patches



(b)

Middle Layer: Metal Via Holes



(c)

Bottom Surface: CPW Feed Line

SRR-Like Planar Antenna

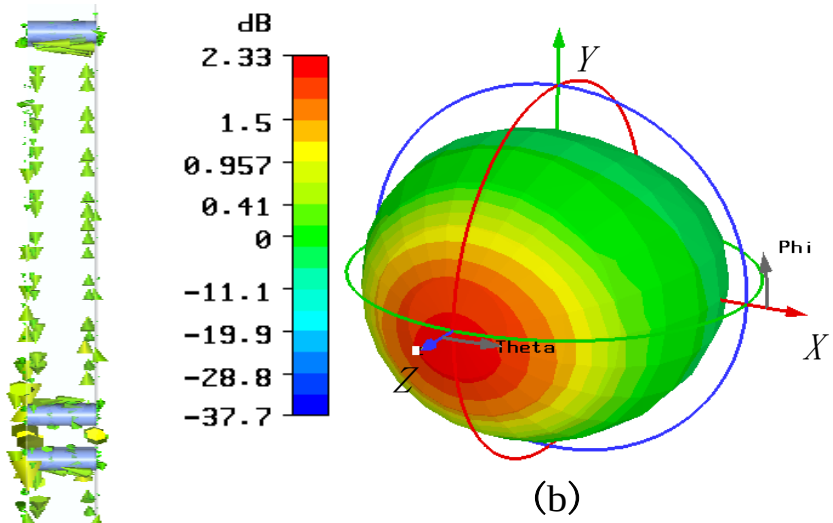
l_1=20mm, l_2=22mm,

Substrate: F4B (epr=2.65)

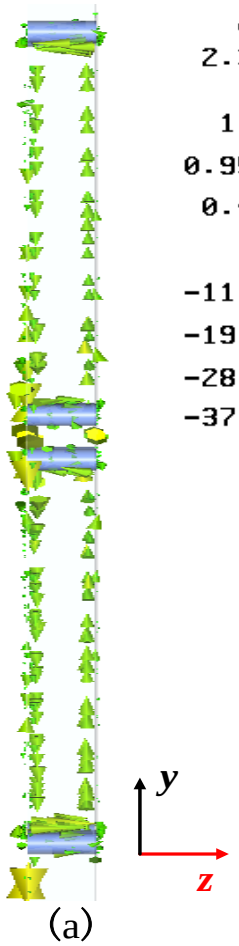
Substrate thickness: 0.8mm

Small Resonant Antennas

M. Li, T. J. Cui, et al., IEEE Antennas and Wireless Propagation Letters, vol. 7, pp. 629-631, 2008.



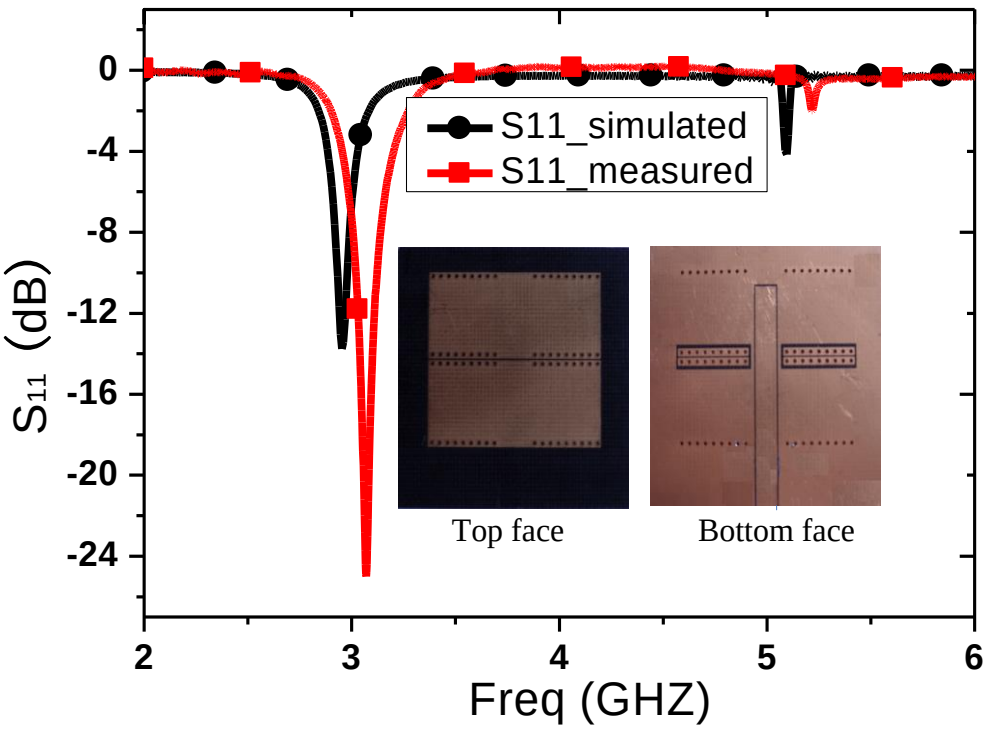
(b)



(a)

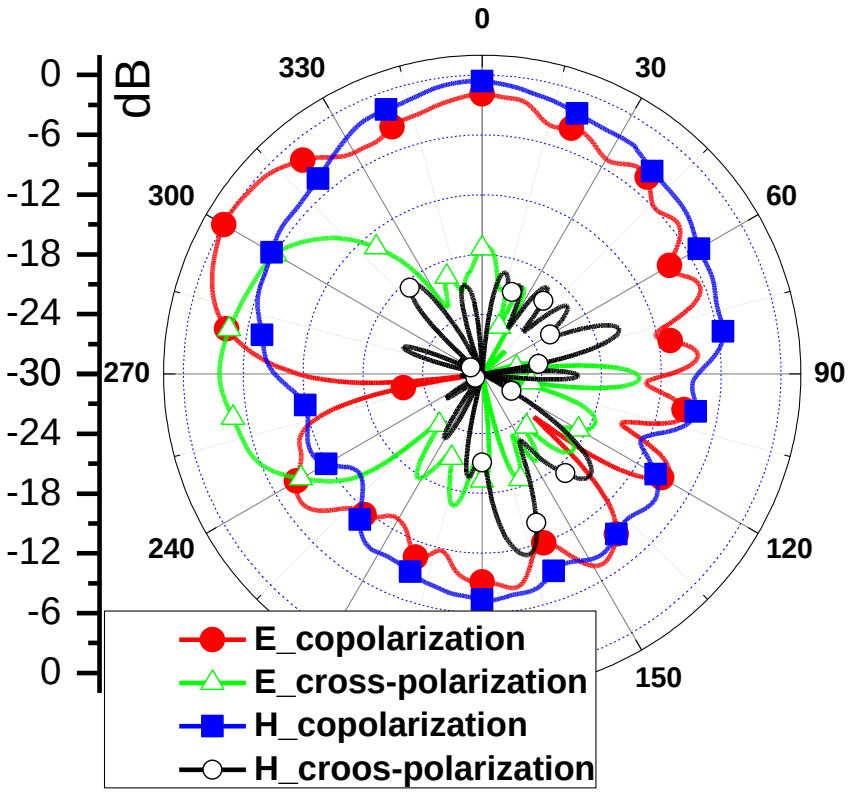
(a)The loop-current distribution along the SRR-based antenna.

(a) The simulated 3D radiation pattern and antenna gain.



Simulation: 2.95GHz, return loss -13.76dB
Measured: 3.06GHz, return loss -24.95dB

Small Resonant Antennas

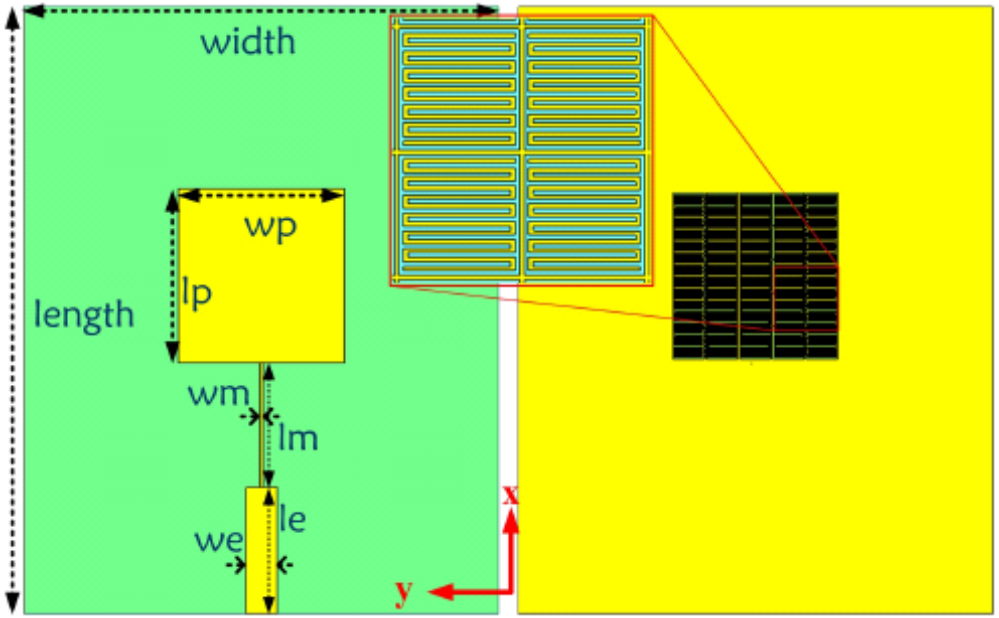


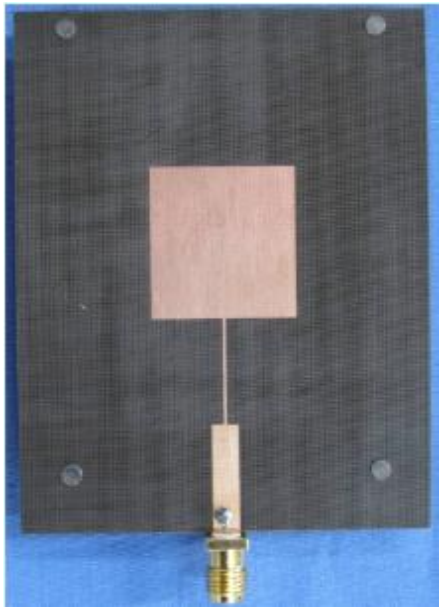
G_{max} is the fundamental limitation of the electrically small antenna

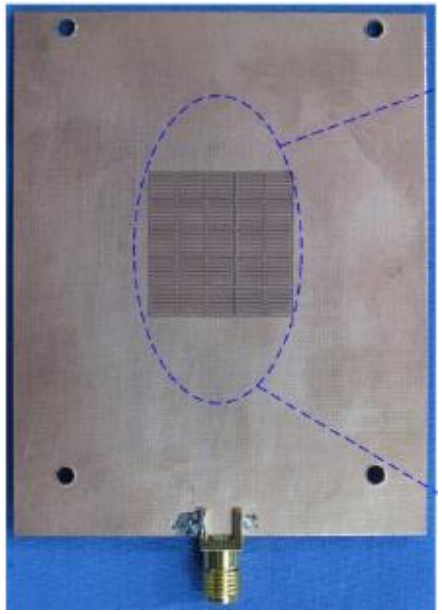
$$G_{\max} = k_0^2 a^2 + 2k_0 a$$

	Simulated	Measured
Freq	2.953GHZ	3.060GHZ
VSWR	1.516	1.143
SIZE	0.197λ×0.217×0.0079λ	0.204λ×0.224×0.0081λ
FBW(-10dB)	1.60%	3.36%
a	0.144λ	0.151λ
Q_{chu}	2.426	2.219
Q_{rad}	62.50	29.76
G_{max}	4.09dB	3.80dB
Gain	2.65dB	2.81dB

Substrate of Patch Antenna







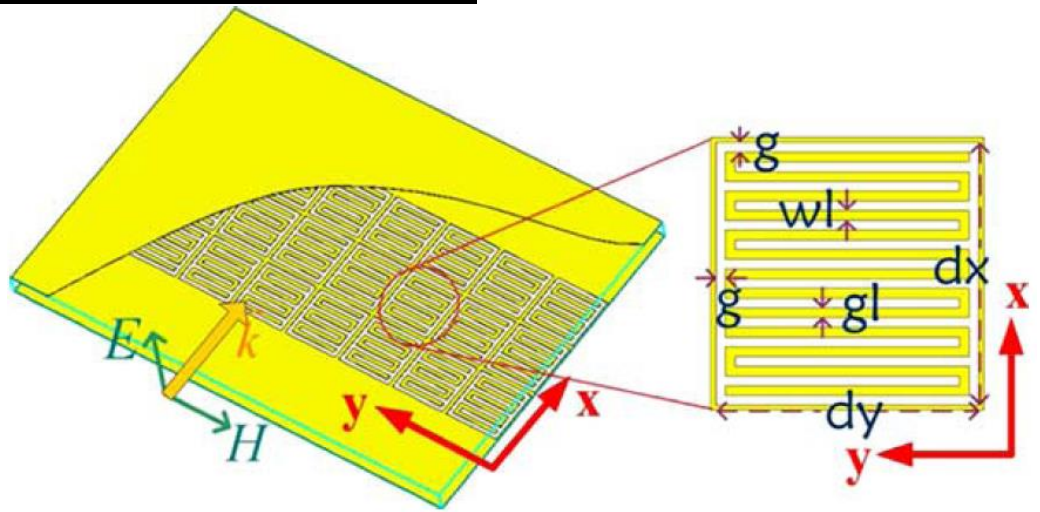
Artificial magneto-dielectric substrate: increase the permeability and decrease the permittivity, to get a better impedance matching, and to increase the bandwidth of the antenna.

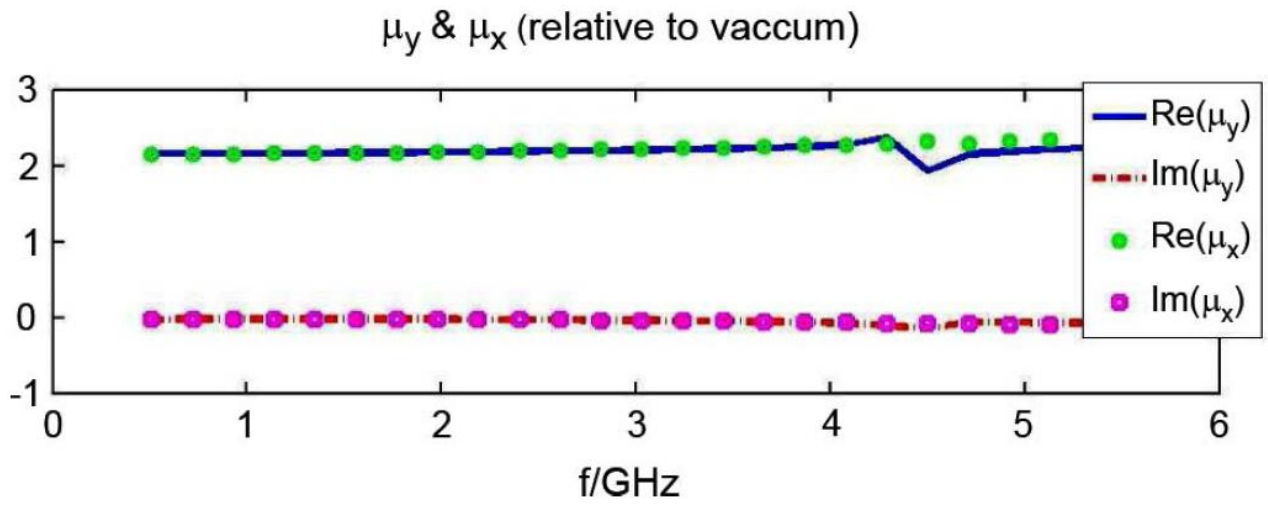
X. M. Yang, T. J. Cui, et al., IEEE Transactions on Antennas and Propagation, vol. 59, pp. 373-378, 2011.

Substrate of Patch Antenna

From the analysis of microsrip antenna:

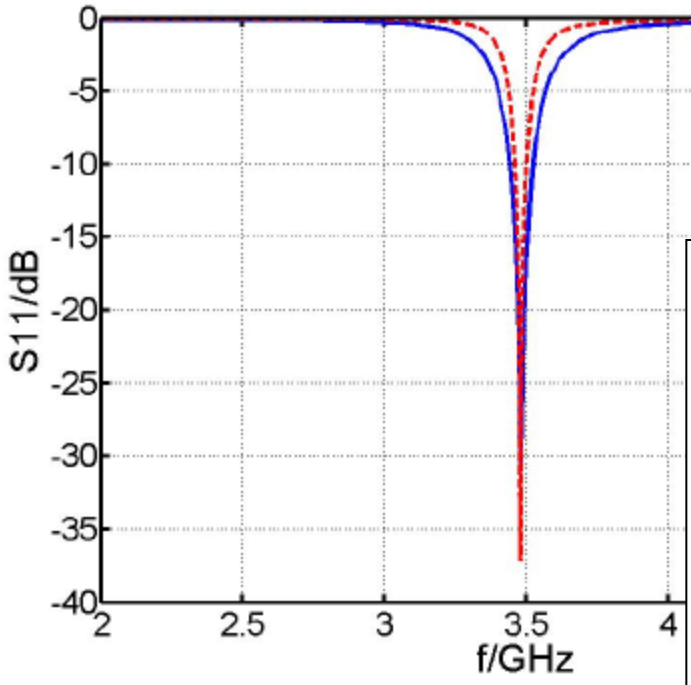
$$BW \approx \frac{96\sqrt{\frac{\mu_c}{\epsilon_c}}\frac{h}{\lambda_0}}{\sqrt{2}[4+17\sqrt{\mu_c\epsilon_c}]}$$

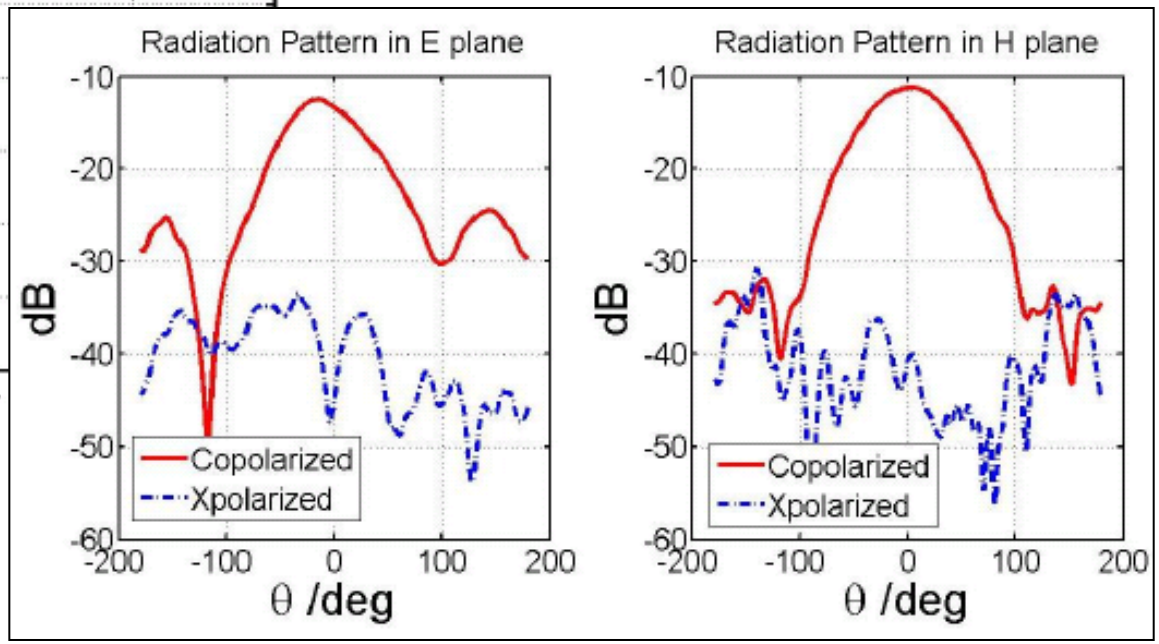




Nearly isotropic in the *x* and *y* directions

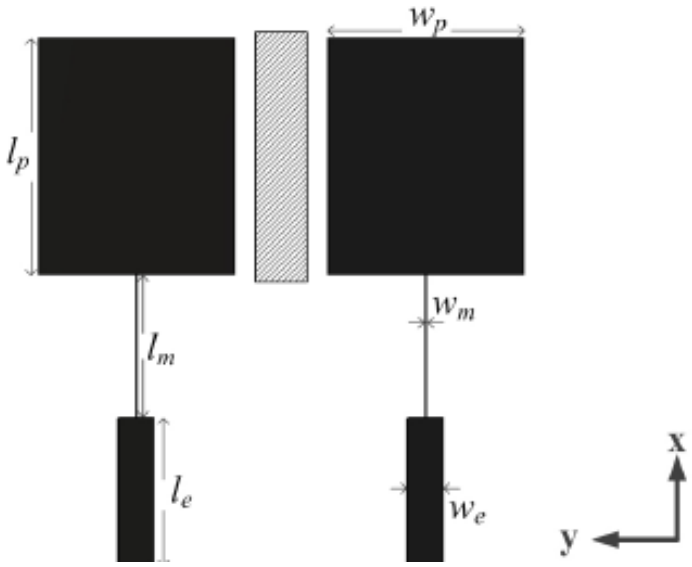
Substrate of Patch Antenna





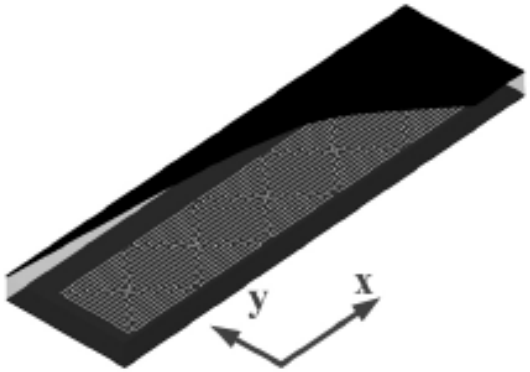
The -10dB bandwidth has been increased from 43 MHz to 84 MHz.

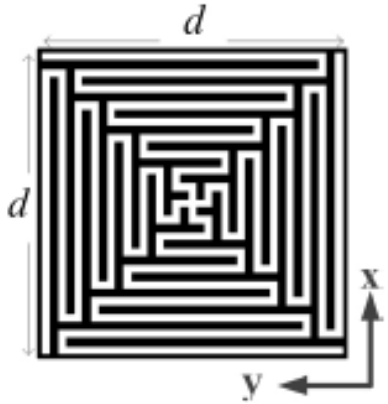
Reduction of Mutual Coupling



Antenna array in wireless communications (MIMO):

Small size; Strong mutual coupling



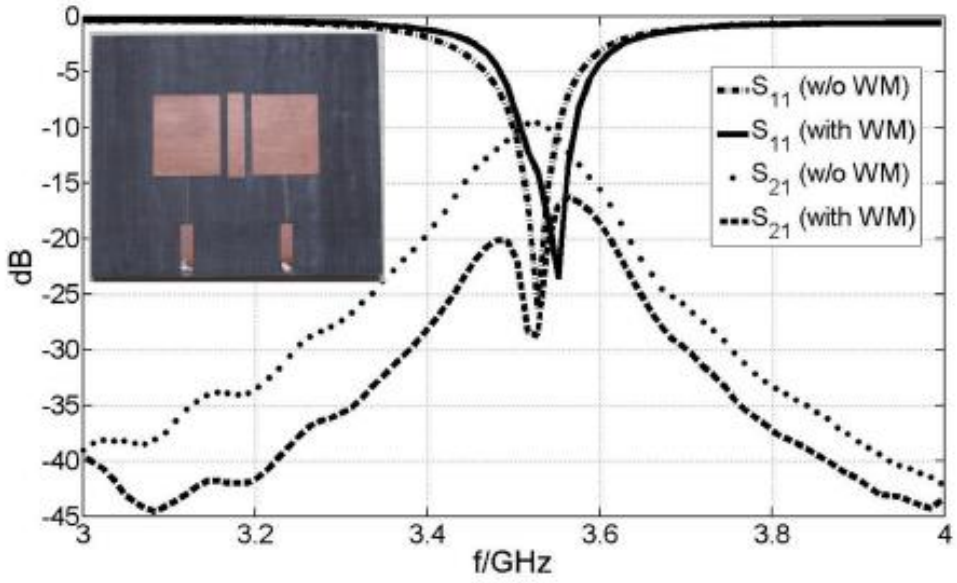


The antennas are separated by λ/8

- **Waveguided Metamaterials Composed of Orthogonal Meander Line Array**
- **Magnetic Resonance, Band-Gap Property**

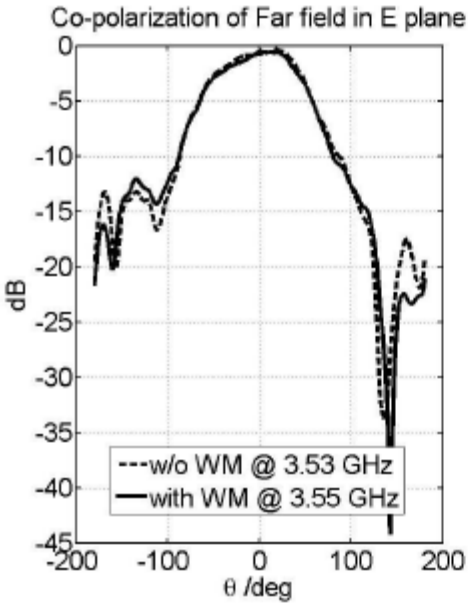
X. M. Yang, T. J. Cui, et al., IEEE Antennas and Wireless Propagation Letters, vol. 11, pp. 389-392, 2012.

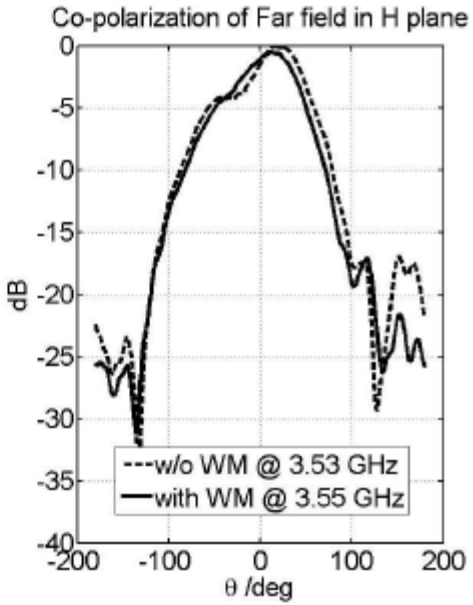
Reduction of Mutual Coupling



Return Loss and Mutual Coupling

Far-Field Radiation Patterns in E and H Planes





The Mutual Coupling is reduced significantly after using the waveguided metamaterials

Anisotropic Zero-Index Material (AZIM) Antennas

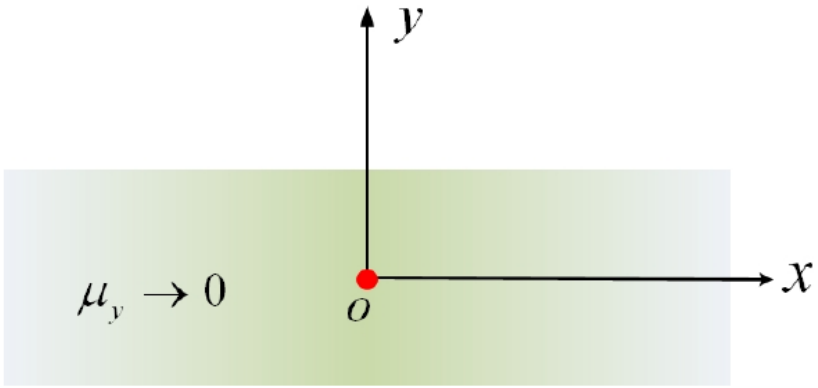
Why AZIM?

- Easy Realization;
- Easy Impedance Matching;
- New Physical Features.

How AZIM?

- Cartesian Coordinate
- Cylindrical Coordinate
- Spherical Coordinate

Cartesian AZIM



When $\mu_y \to 0$

We have E_z be constant along the *x* direction

$$\frac{k_x^2}{\mu_y} + \frac{k_y^2}{\mu_x} = \frac{\omega^2}{c^2}\epsilon_z$$

$$k_x \to 0$$

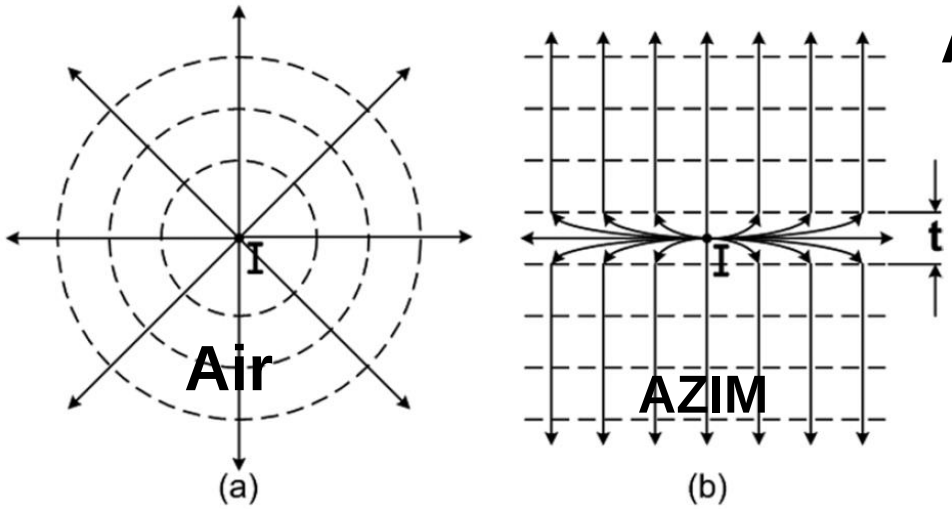
$$k_y = (\omega/c)\sqrt{\epsilon_z \mu_x}$$

$$\frac{\partial E_z}{\partial x} = -i\omega\mu_y H_y$$

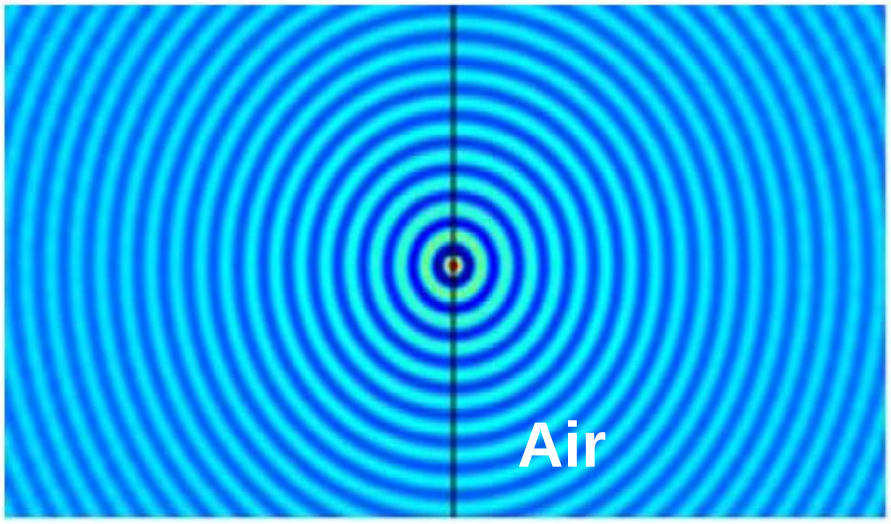
Therefore, only plane waves propagating along the y direction are supported in such AZIM.

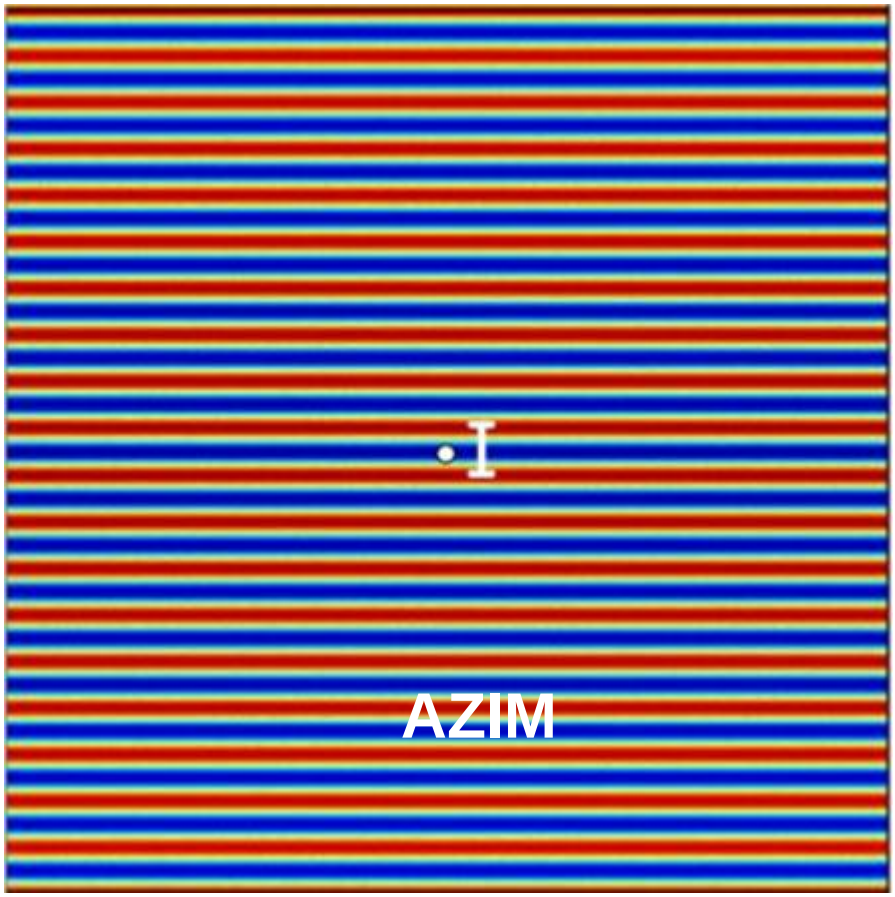
Q. Cheng, T. J. Cui, W. X. Jiang, Journal of Physics D: Applied Physics, vol. 43, 335406, 2010.

Cartesian AZIM



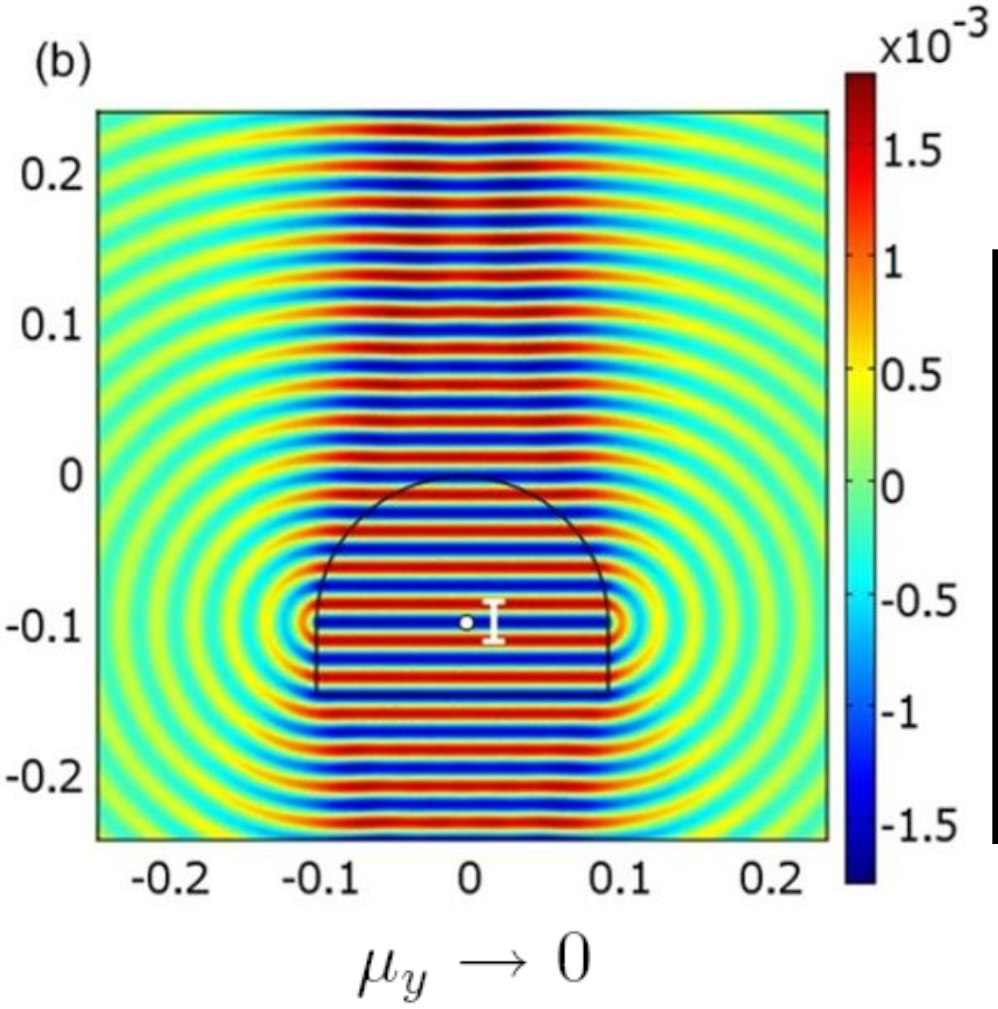
A Line Source in Infinite AZIM





Cartesian AZIM

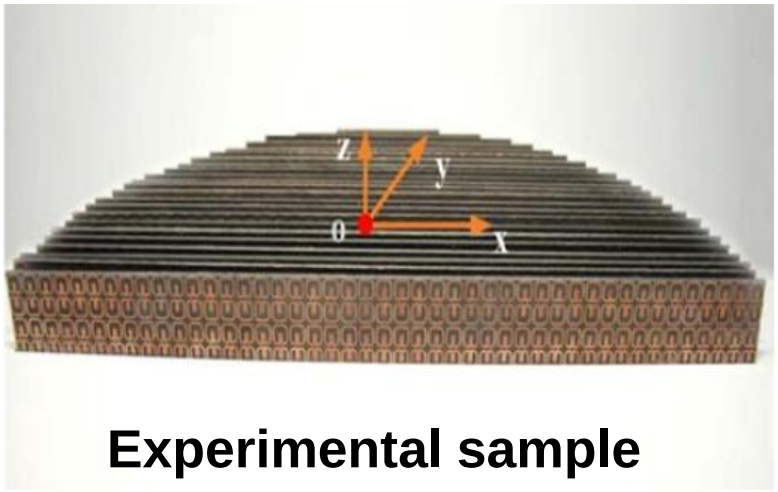
A Line Source in Finite AZIM



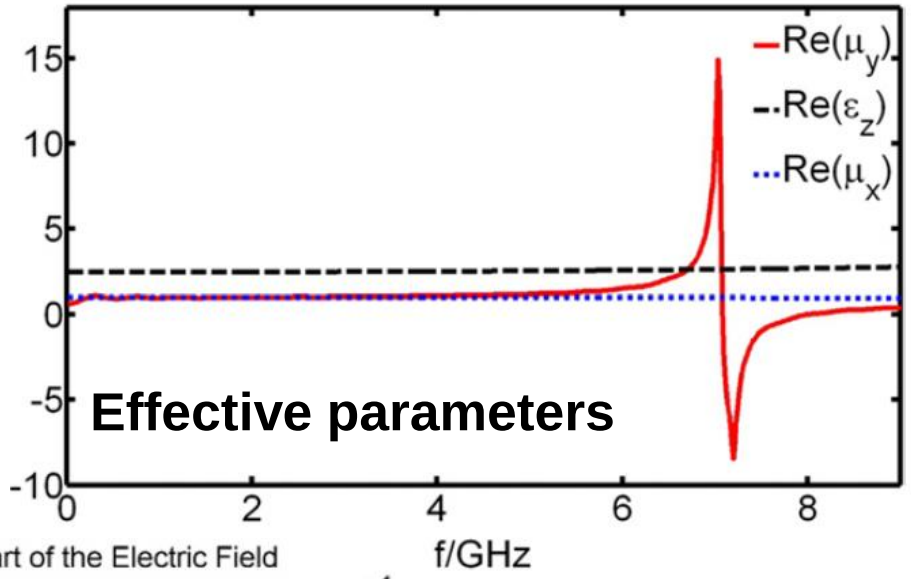
Very Important Feature:

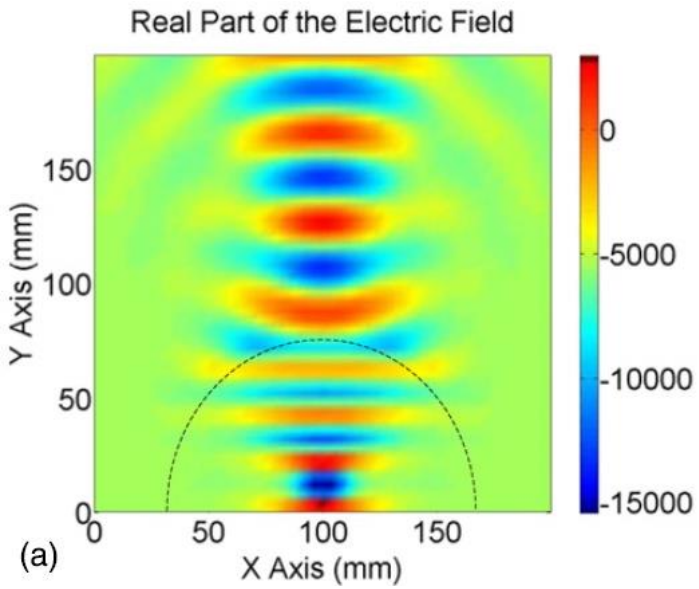
The plane-wave front is larger than the actual aperture, which makes it possible to break the limitation of antenna gain!

Cartesian AZIM

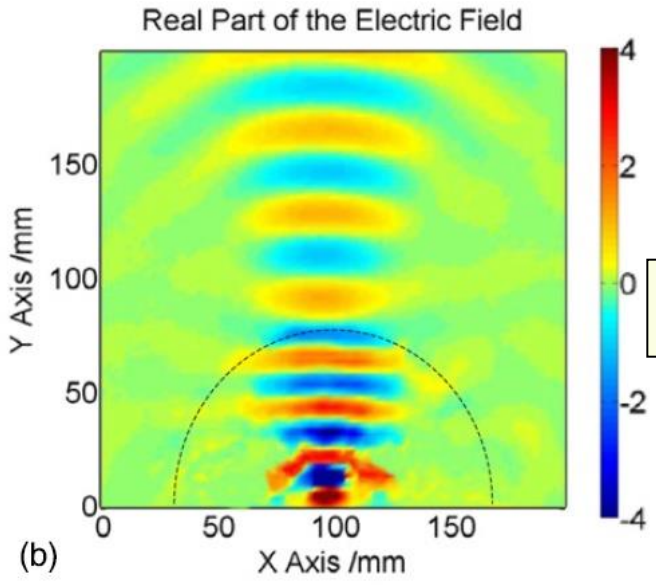


Experimental sample





Simulation

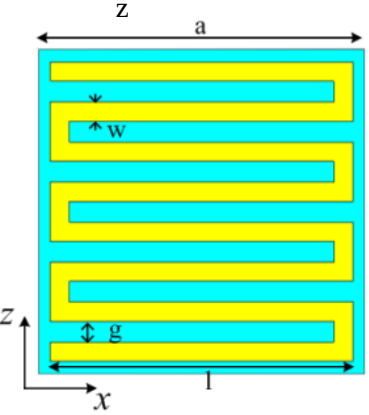


Measurement

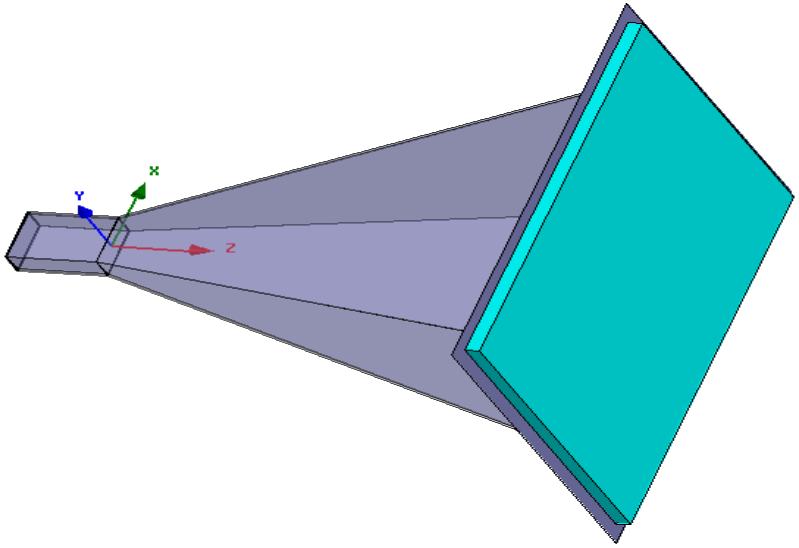
$\mu_y \rightarrow 0$ at f=8GHz

3D AZIM Antenna

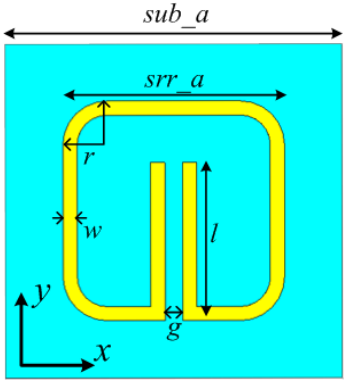
$\varepsilon_z \to 0$



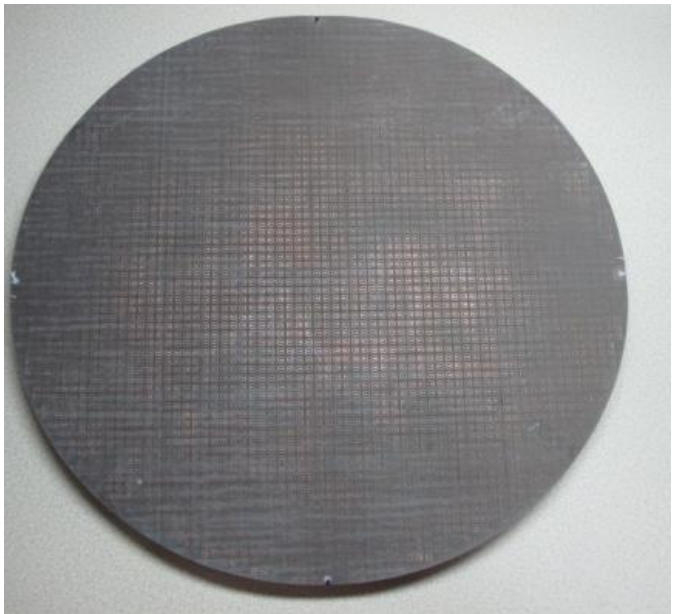
Narrow E face



$\mu_z \to 0$

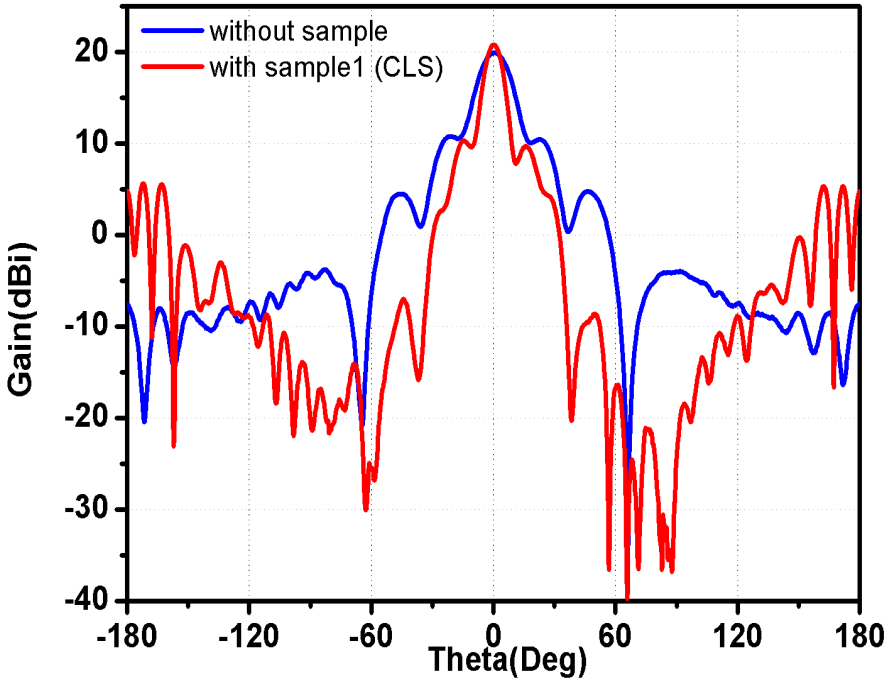


Narrow H face

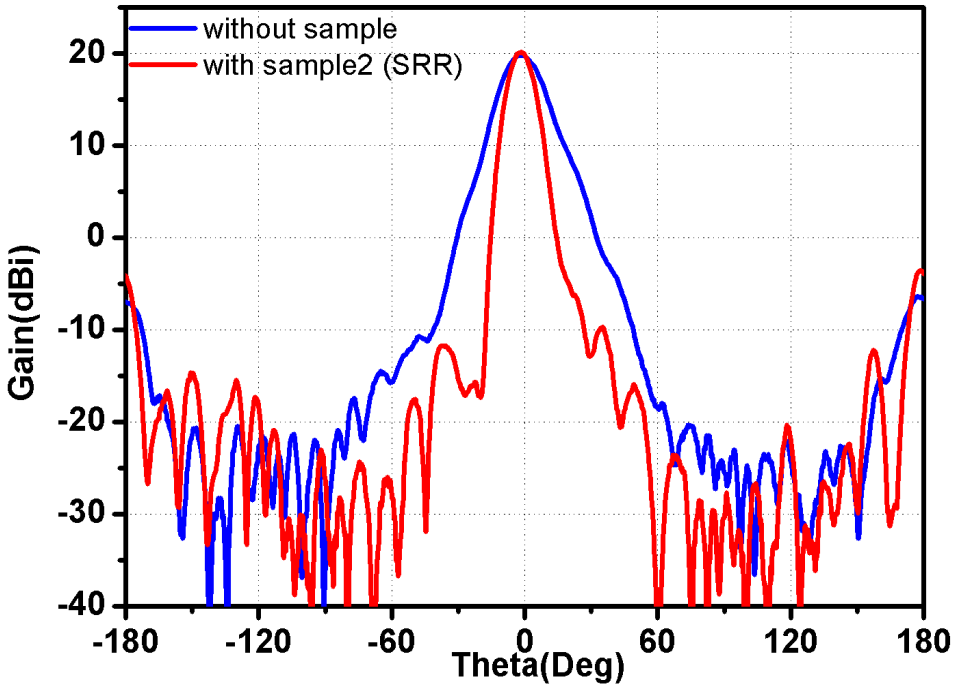


L. H. Yuan, T. J. Cui, et al.,
IEEE Transactions on Antennas and Propagation,
vol. 62, pp. 4135-4142,(2014).

3D AZIM Antenna



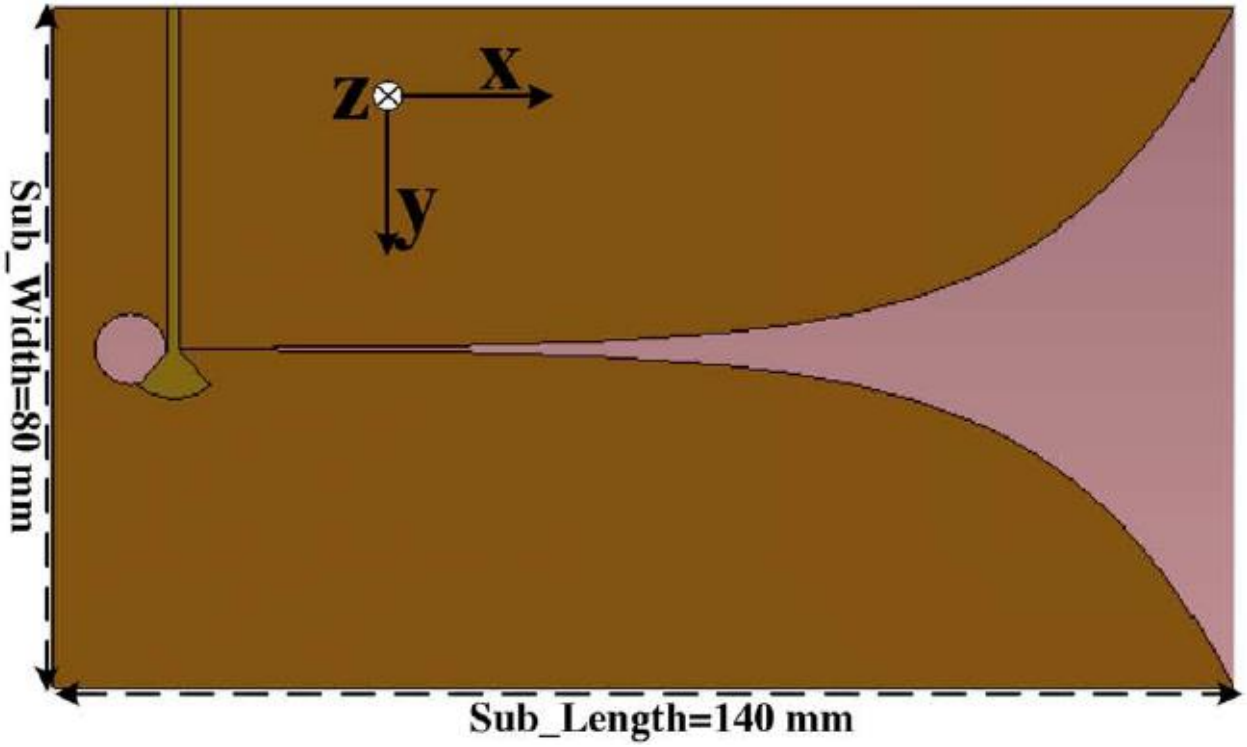
E face with ε→0



H face with μ→0

Increase the directivity and decrease the beamwidth of antenna significantly.

3D homogeneous AZIM Planar Antenna

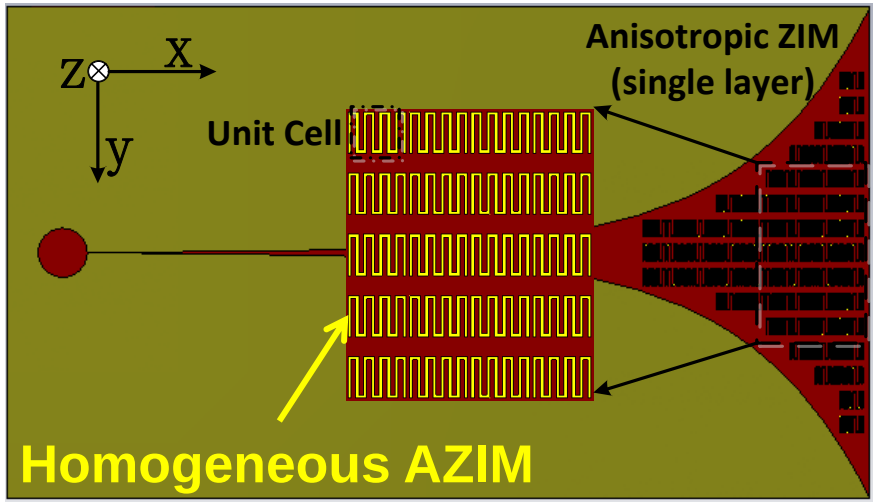


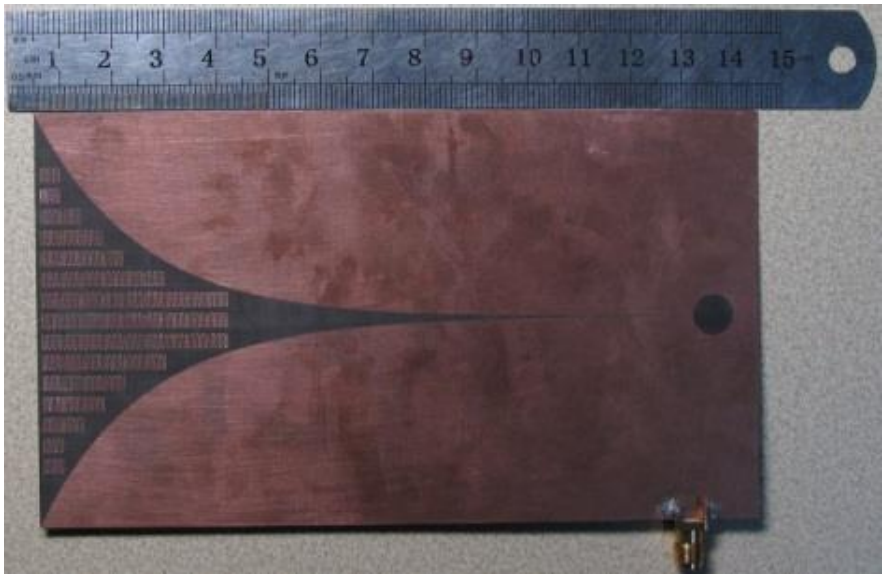
Vivaldi Antenna: Ultra Wideband but Low Gain

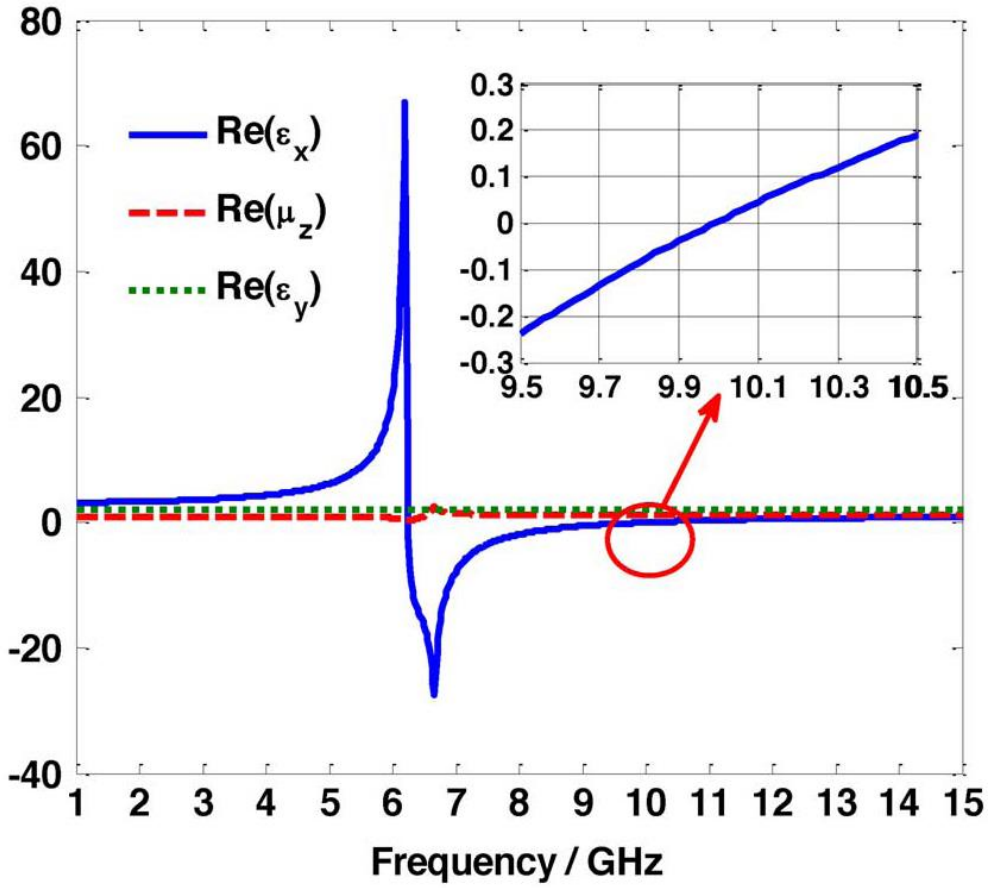
Antenna Constraint

B. Zhou and T. J. Cui, IEEE Antennas and Wireless Propagation Letters, vol. 10, pp. 326-330, 2011

3D homogeneous AZIM Planar Antenna

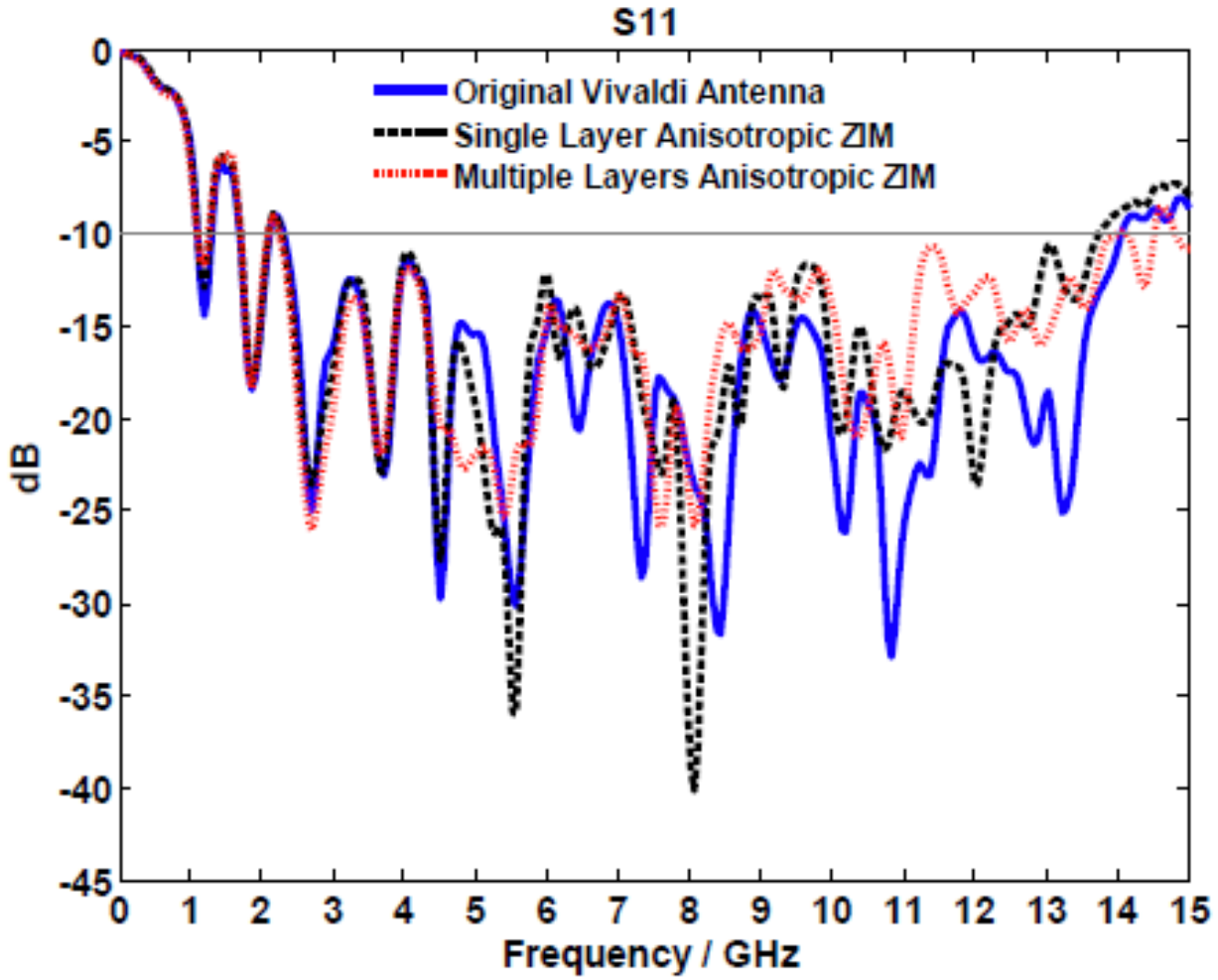




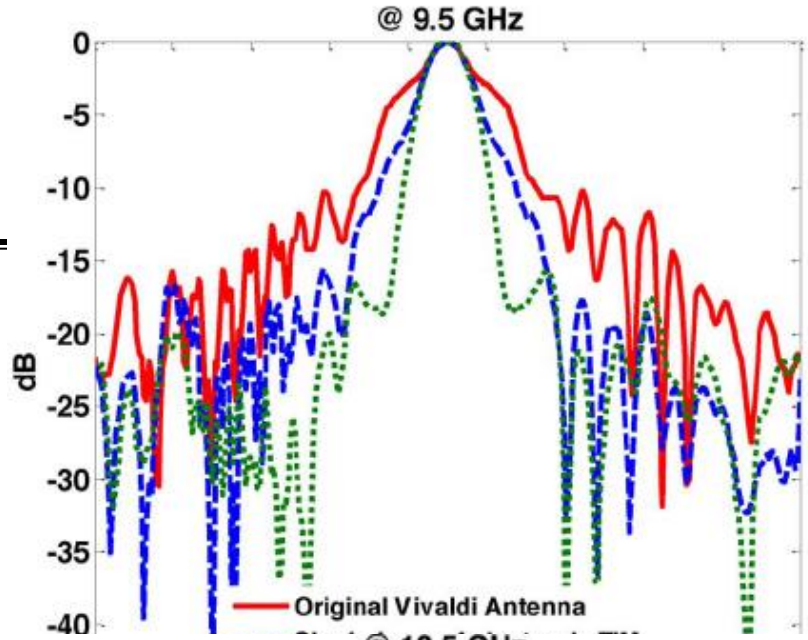


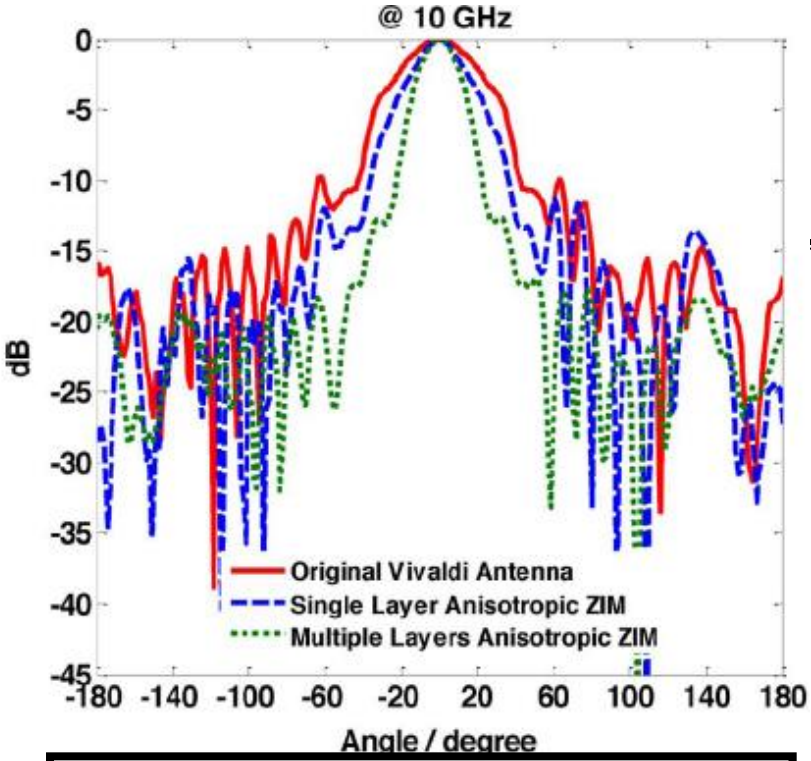
$\mu_x \rightarrow 0$ at f=10GHz

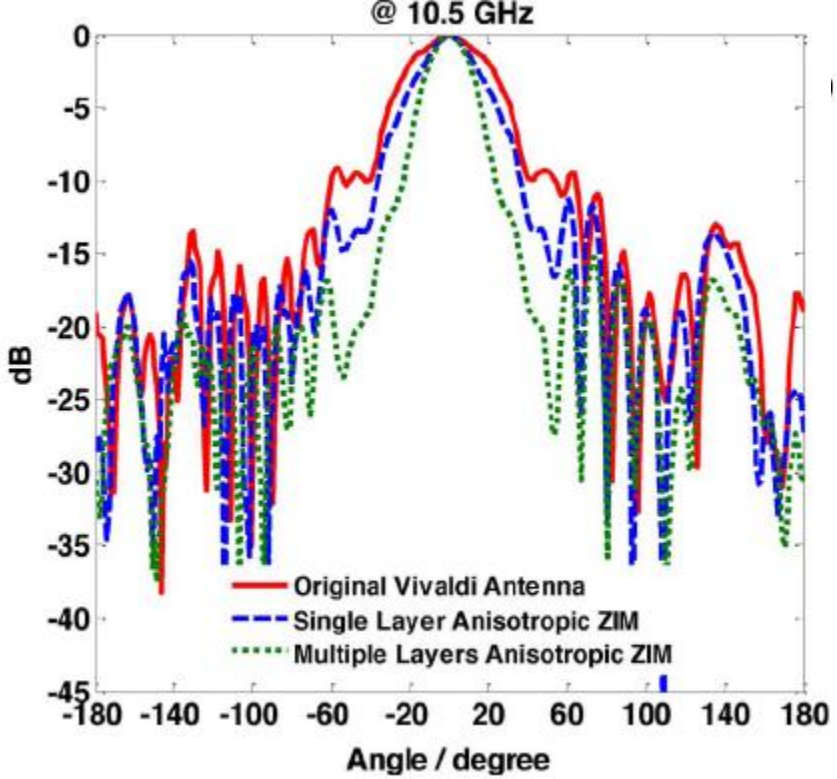
3D homogeneous AZIM Planar Antenna

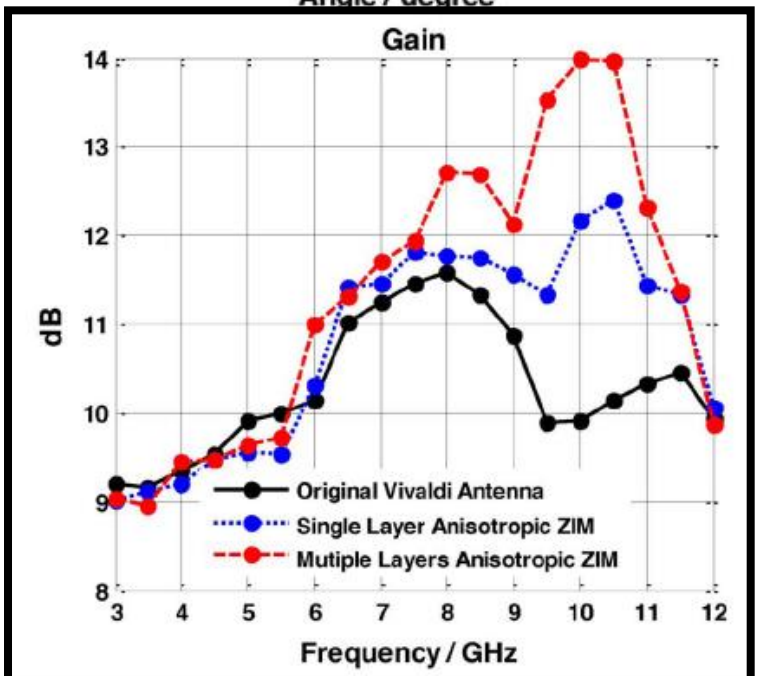


Measured S11 parameters

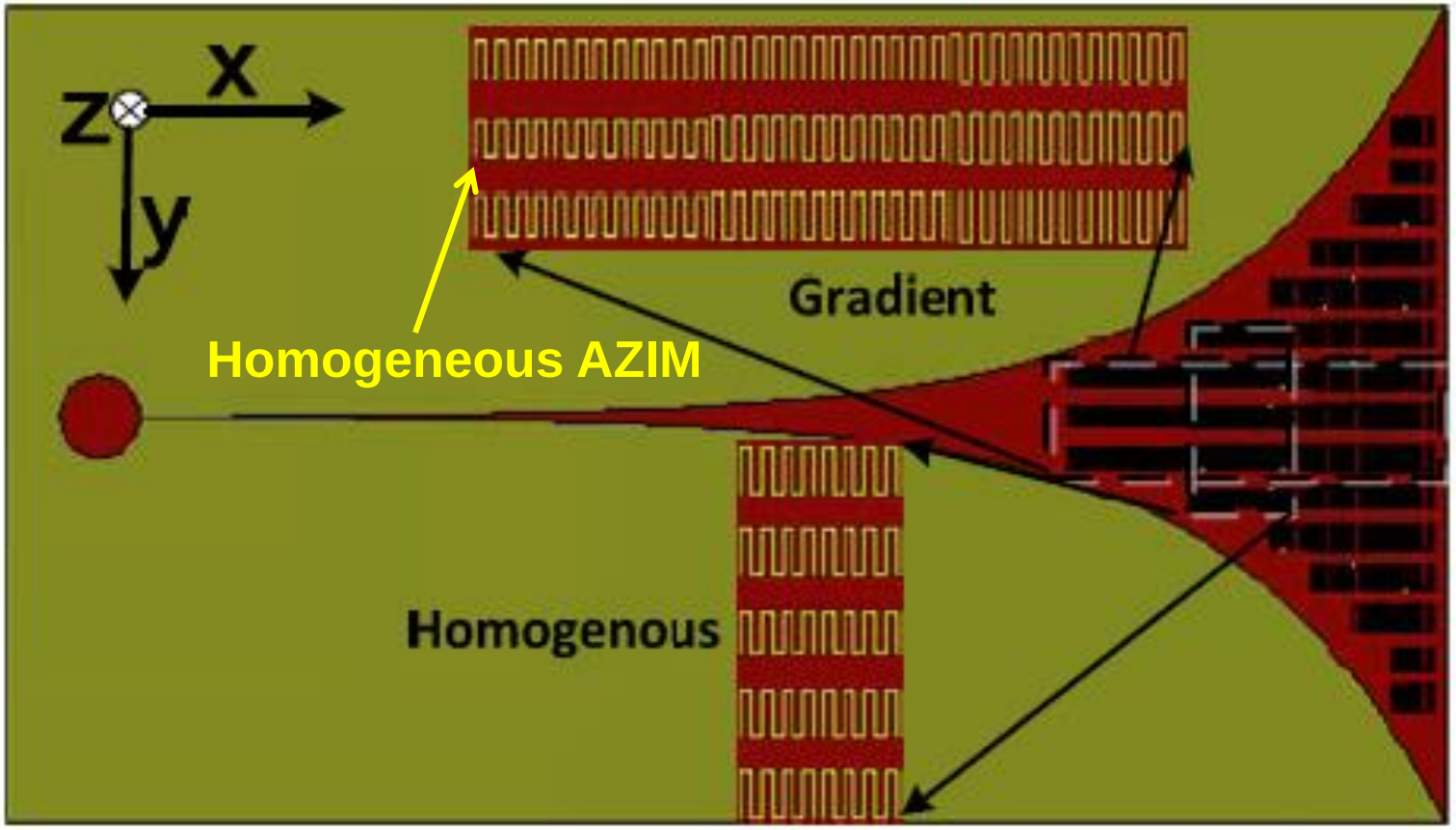

@ 9.5 GHz
dB
Original Vivaldi Antenna


@ 10 GHz
dB
Original Vivaldi Antenna
Single Layer Anisotropic ZIM
Multiple Layers Anisotropic ZIM
Angle / degree


@ 10.5 GHz
dB
Original Vivaldi Antenna
Single Layer Anisotropic ZIM
Multiple Layers Anisotropic ZIM
Angle / degree

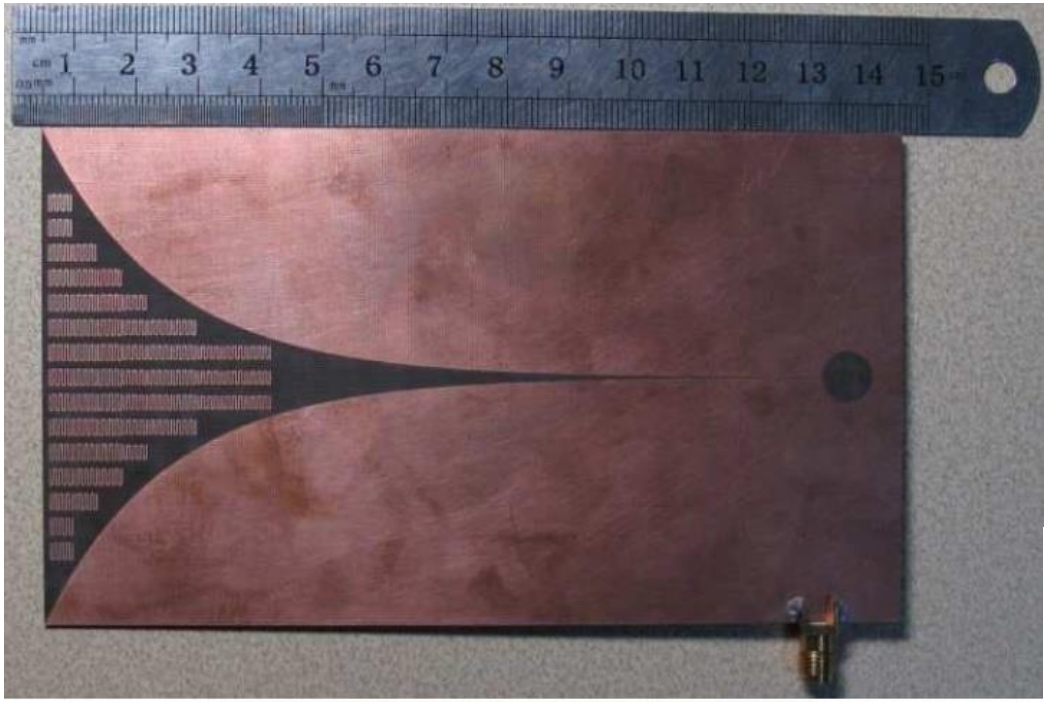

Gain
dB
Original Vivaldi Antenna
Single Layer Anisotropic ZIM
Mutiple Layers Anisotropic ZIM
Frequency / GHz

3D Inhomogeneous AZIM Planar Antenna

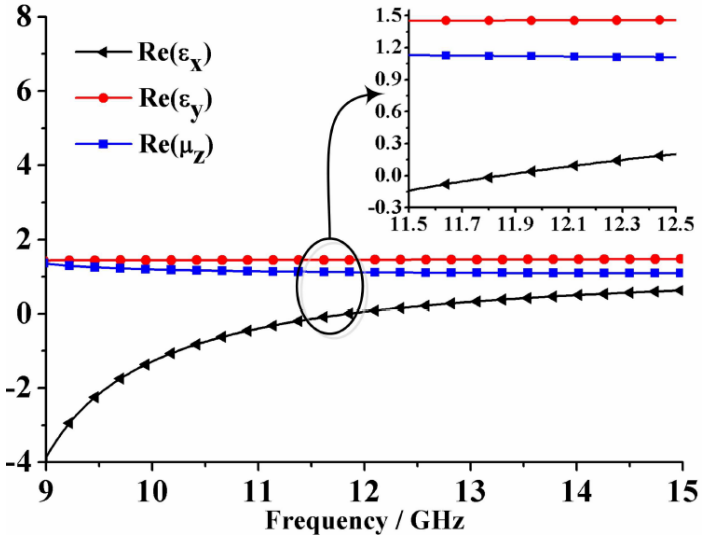


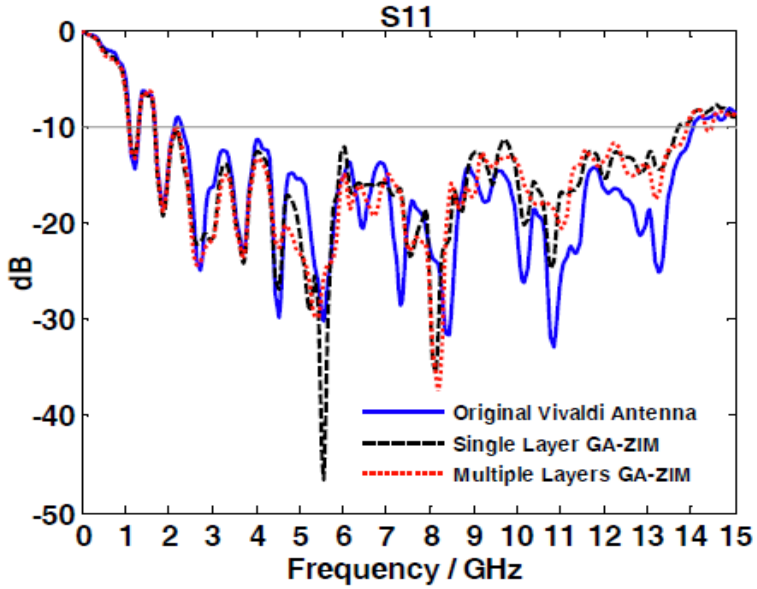
B. Zhou and T. J. Cui,
Progress in Electromagnetics Research (PIER) 120, pp. 275-247, 2011

3D Inhomogeneous AZIM Planar Antenna

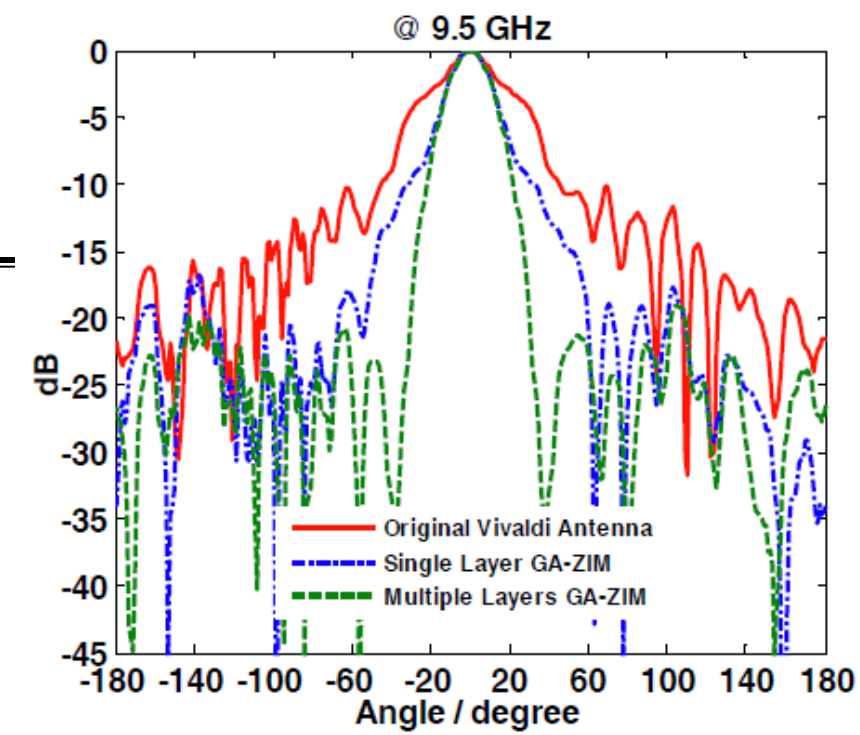


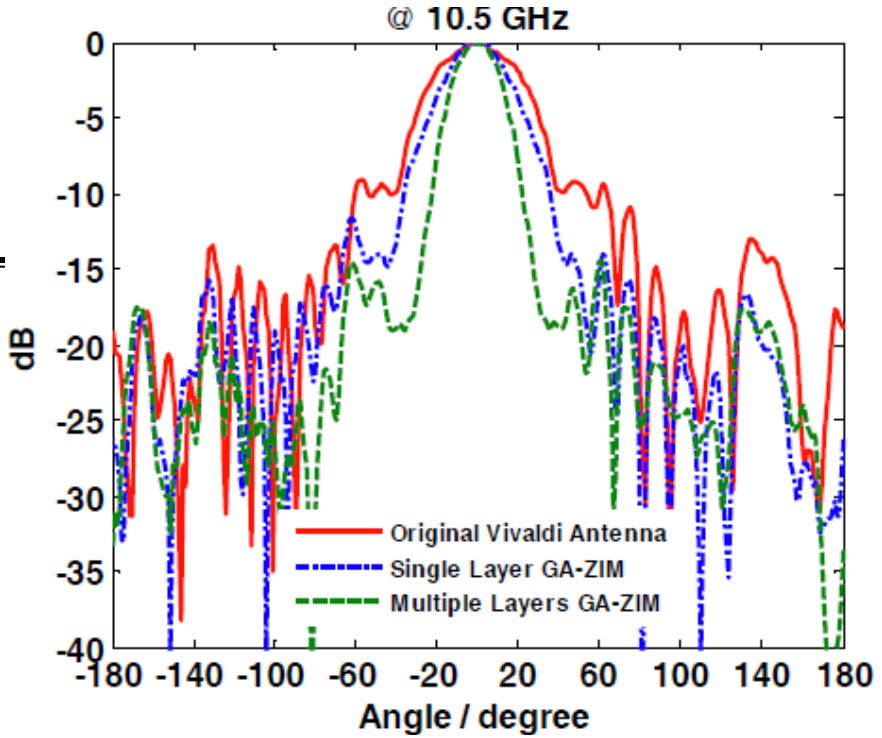
Experimental sample

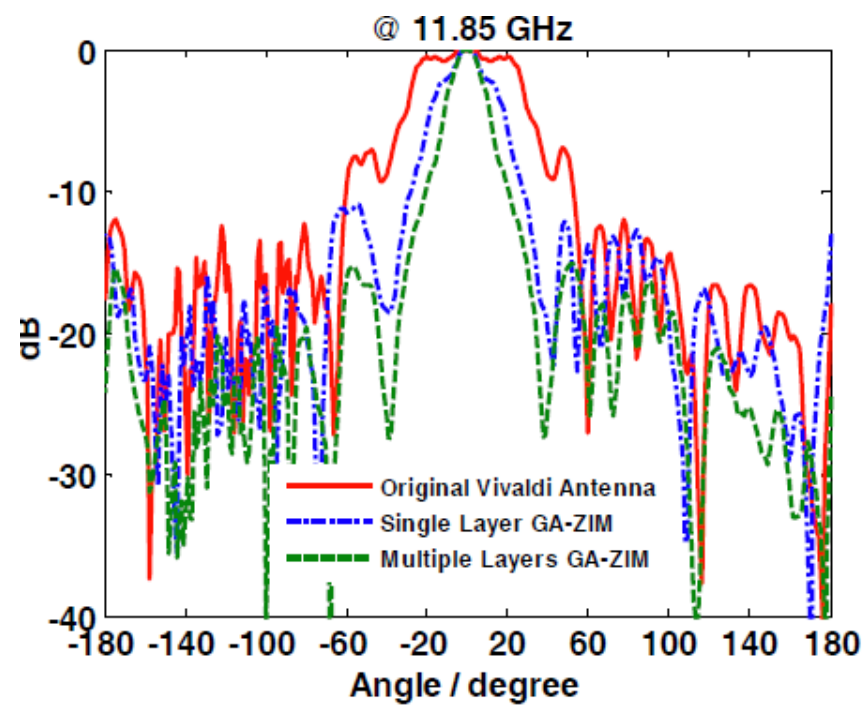


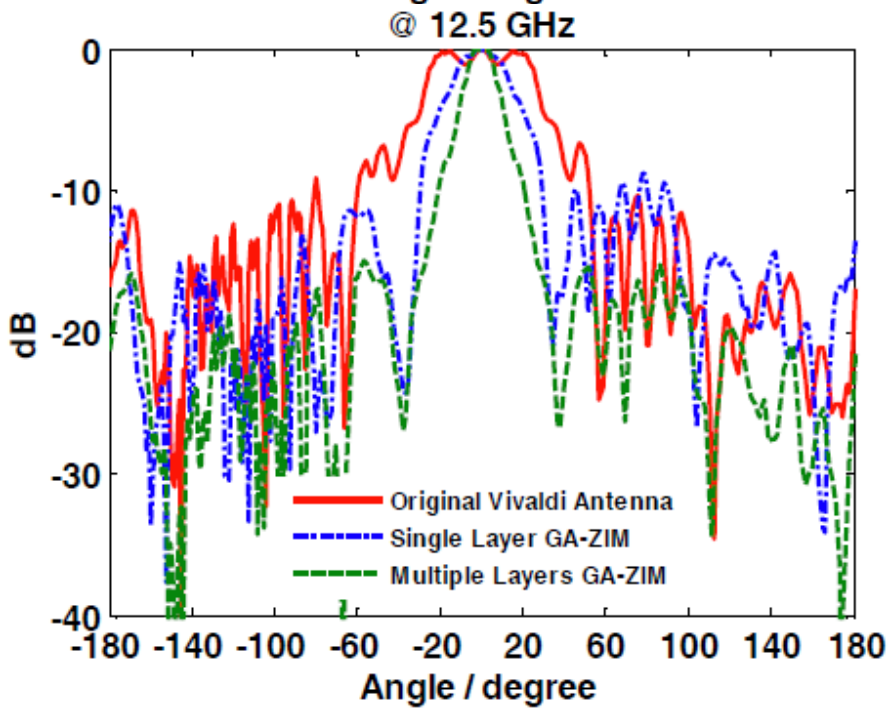


✓ Wider band than homogeneous AZI planar antenna

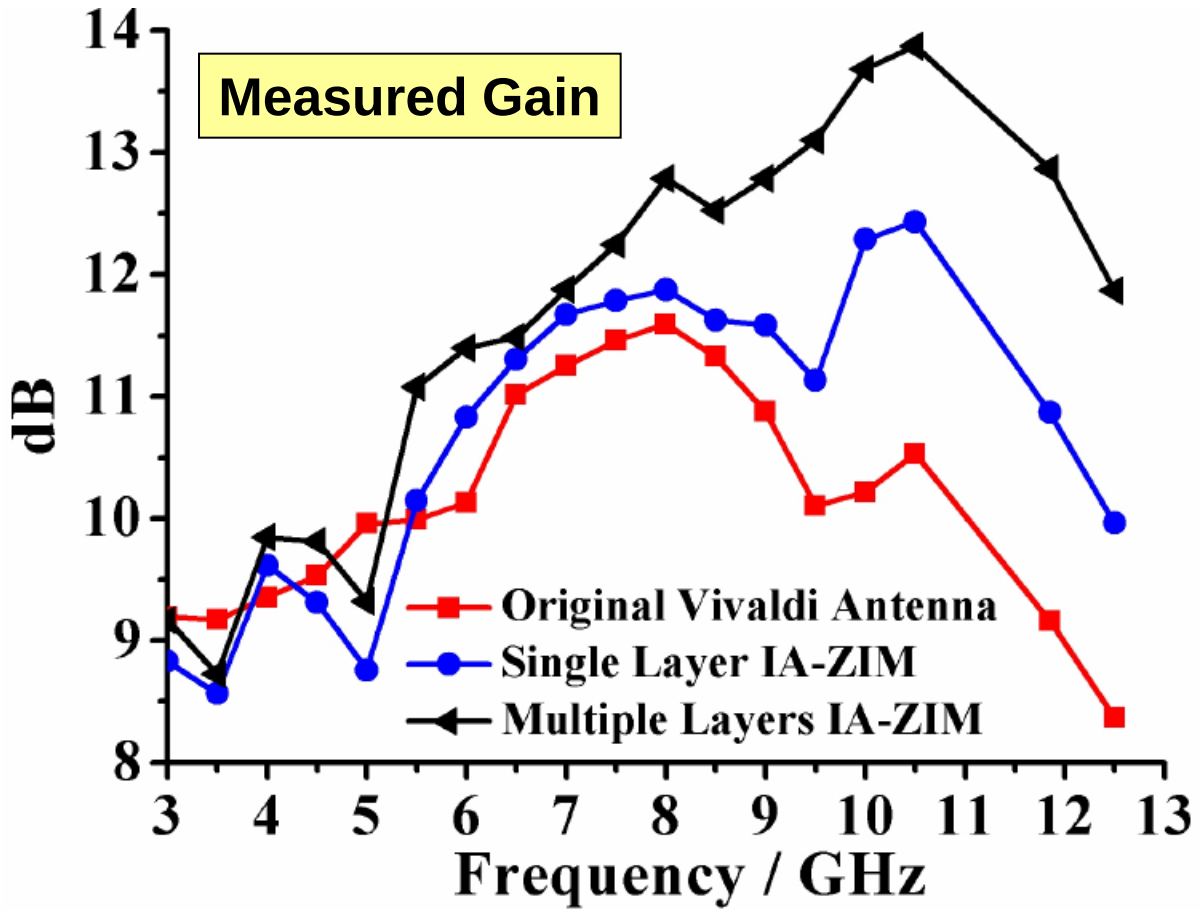

@ 9.5 GHz
dB
Angle / degree
Original Vivaldi Antenna
Single Layer GA-ZIM
Multiple Layers GA-ZIM


@ 10.5 GHz
dB
Angle / degree
Original Vivaldi Antenna
Single Layer GA-ZIM
Multiple Layers GA-ZIM


@ 11.85 GHz
dB
Angle / degree
Original Vivaldi Antenna
Single Layer GA-ZIM
Multiple Layers GA-ZIM


@ 12.5 GHz
dB
Angle / degree
Original Vivaldi Antenna
Single Layer GA-ZIM
Multiple Layers GA-ZIM

Antenna Type	@ 9.5 GHz	@ 10 GHz	@ 10.5 GHz	@ 11.85 GHz	@ 12.5 GHz
Original	40.5°	48.4°	48.7°	55.8°	54.6°
Single layer	24°	27°	36°	26.6°	29.2°
Multiple layers	24°	23.2°	26°	18°	17.6°

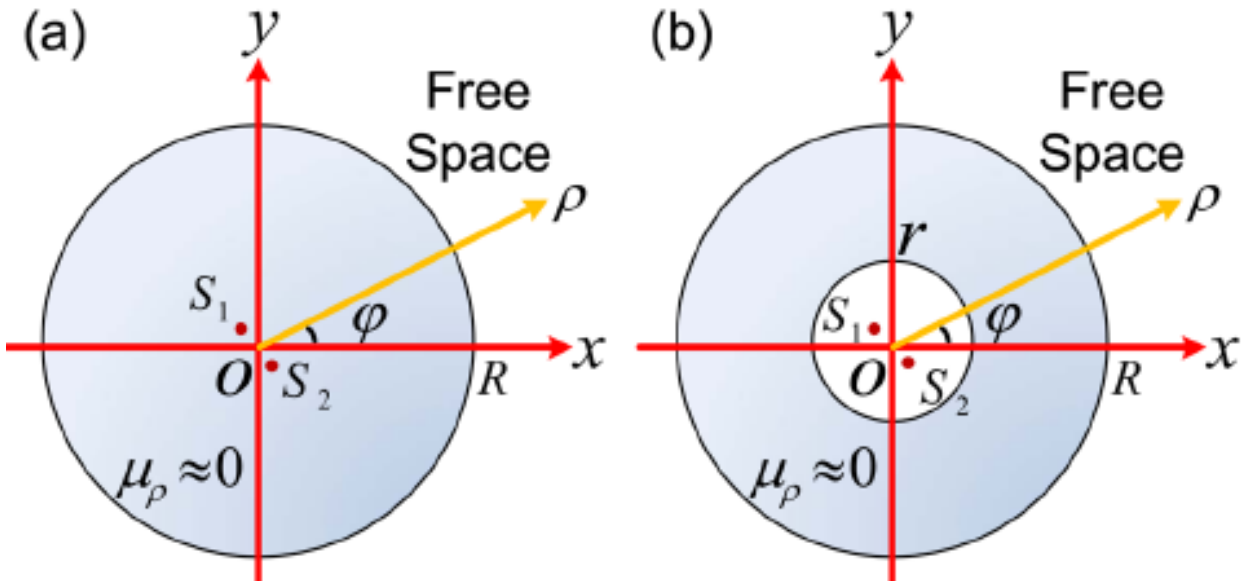


Cylindrical AZIM

PRL 108, 213903 (2012) PHYSICAL REVIEW LETTERS week ending 25 MAY 2012

Spatial Power Combination for Omnidirectional Radiation via Anisotropic Metamaterials

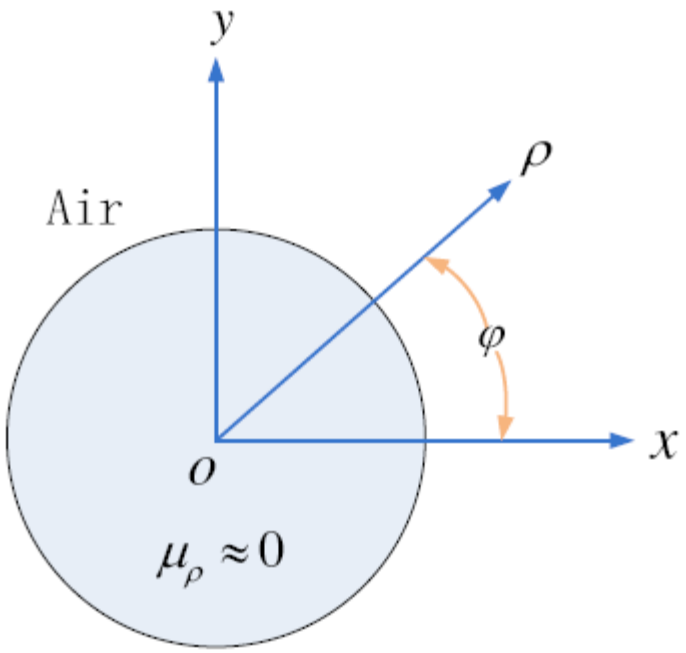
Qiang Cheng, Wei Xiang Jiang, and Tie Jun Cui*



- Omnidirectional Radiations
- Spatial Power Combination

Cylindrical AZIM

◆ TE Polarization



$$\bar{\bar{\varepsilon}} = \hat{\rho}\,\hat{\rho}\,\varepsilon_\rho + \hat{\varphi}\,\hat{\varphi}\,\varepsilon_\varphi + \hat{z}\,\hat{z}\,\varepsilon_z$$

$$\bar{\bar{\mu}} = \hat{\rho}\,\hat{\rho}\,\mu_\rho + \hat{\varphi}\,\hat{\varphi}\,\mu_\varphi + \hat{z}\,\hat{z}\,\mu_z$$

$$\nabla \times \bar{E} = i\omega\bar{\bar{\mu}} \cdot \bar{H}.$$

$$\frac{1}{\rho}\frac{\partial E_z}{\partial \phi} = i\omega\mu_\rho H_\rho$$

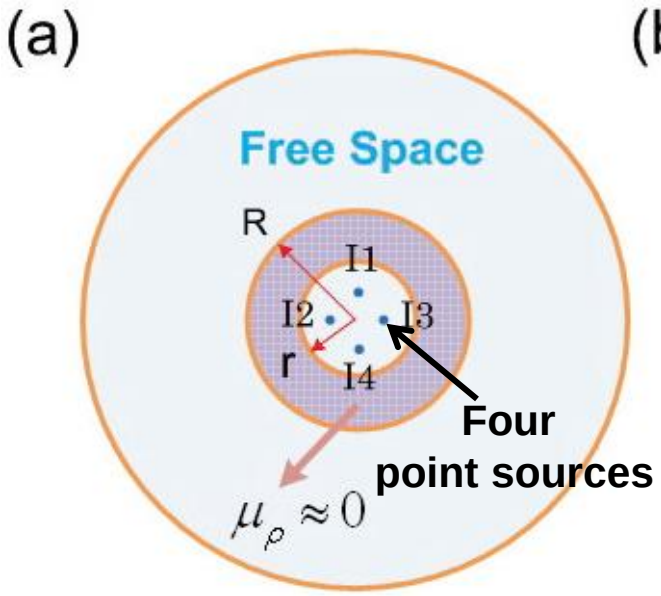
$$\mu_\rho \cong 0$$

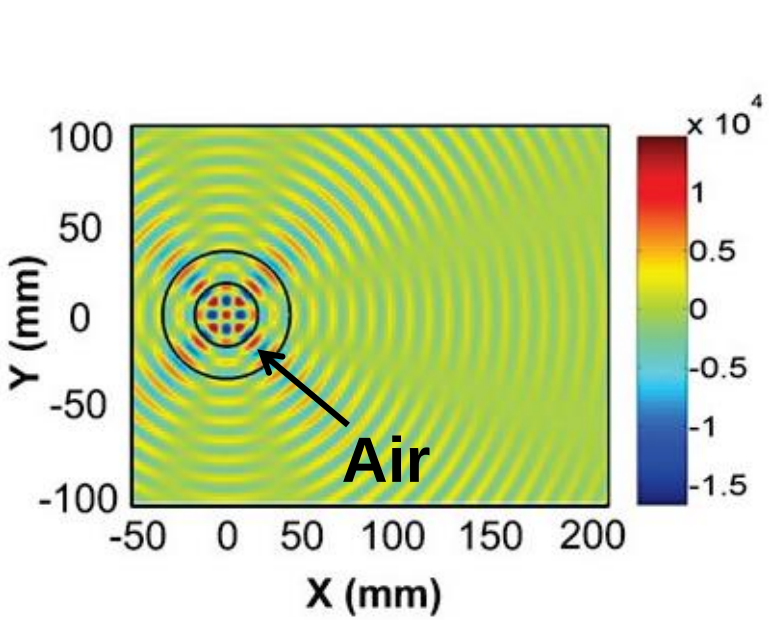
$$\frac{k_\rho^2}{\mu_\phi} + \frac{k_\phi^2}{\mu_\rho} = \omega^2 \epsilon_z$$

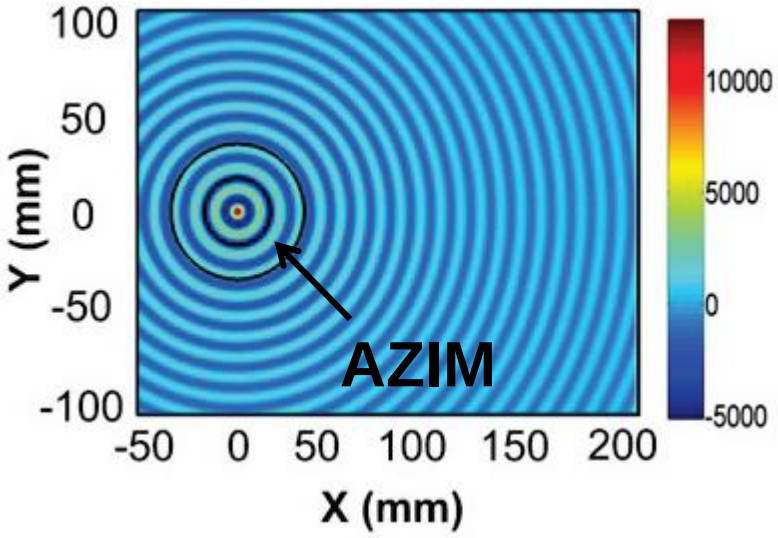
The fields are constants along phi.

$$k_\rho = \omega\sqrt{\epsilon_z \mu_\phi}$$

Cylindrical AZIM

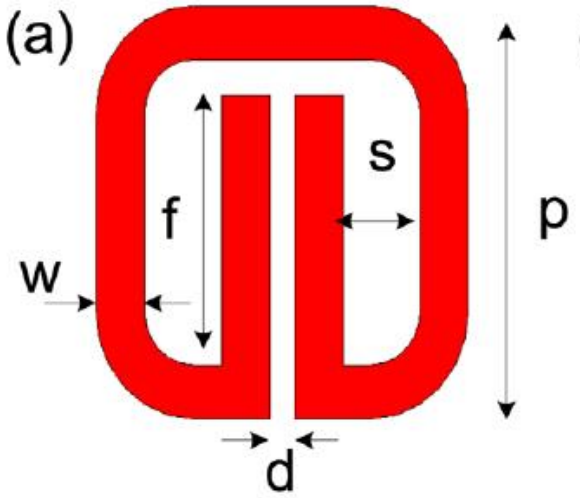




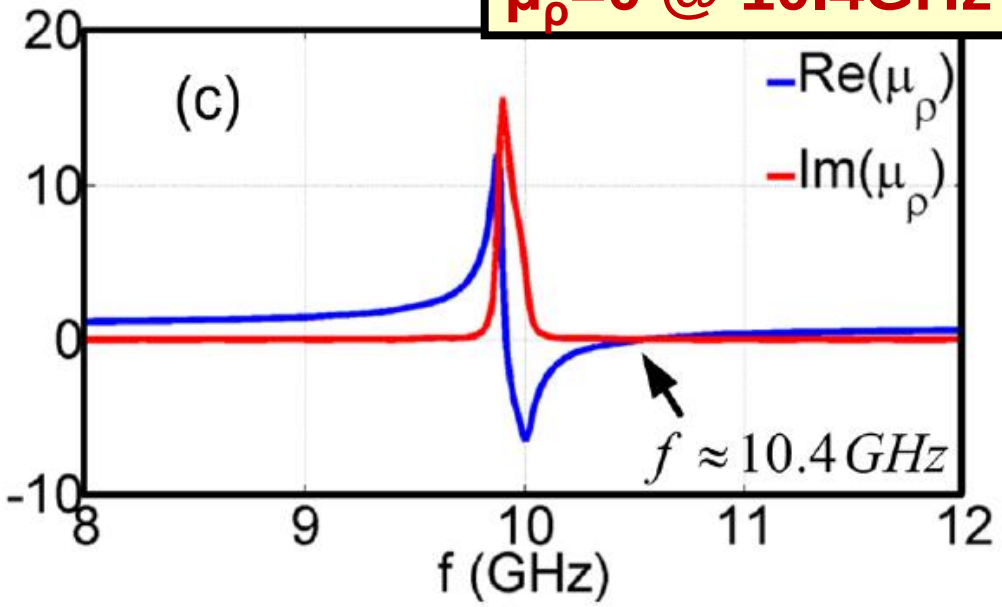


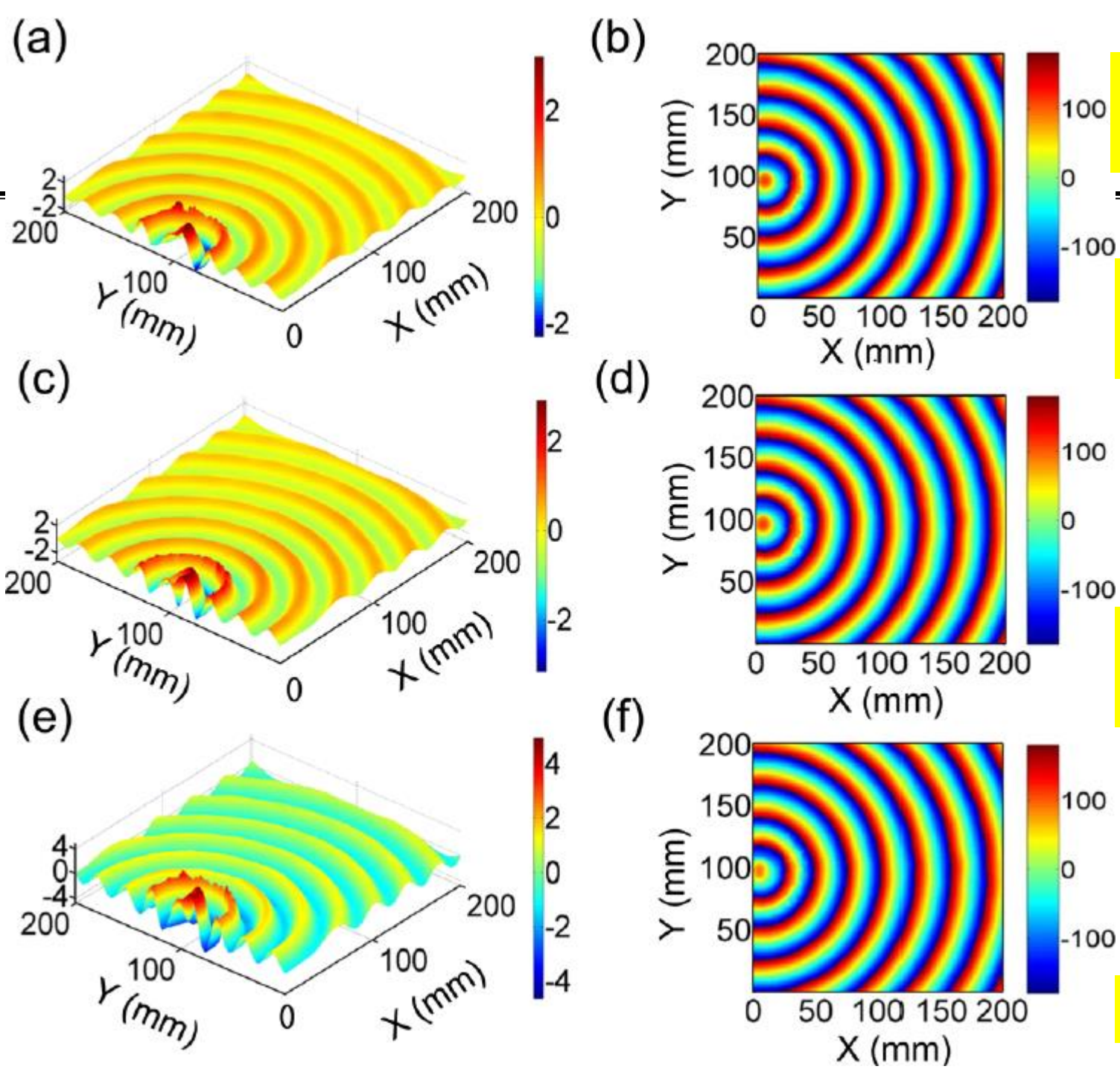
Only cylindrical waves propagating along the rho direction are supported in such AZIM.

Cylindrical AZIM



Experimental sample
μ_ρ=0 @ 10.4GHz





Measurement Results

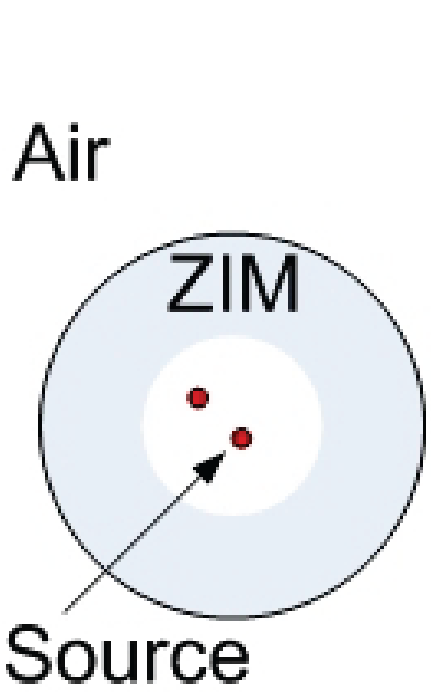
Off-Center Source #1

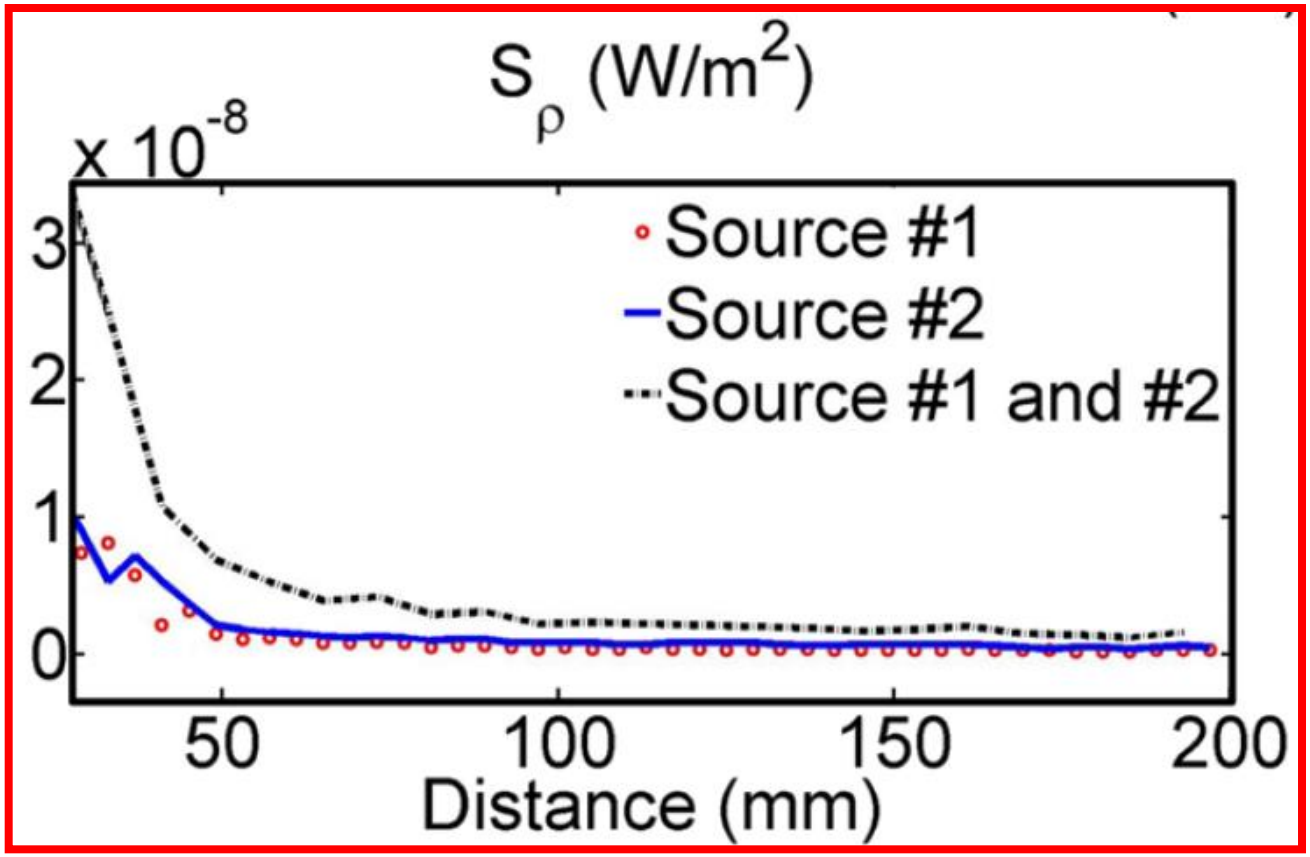
Off-Center Source #2

Two Sources

Cylindrical AZIM

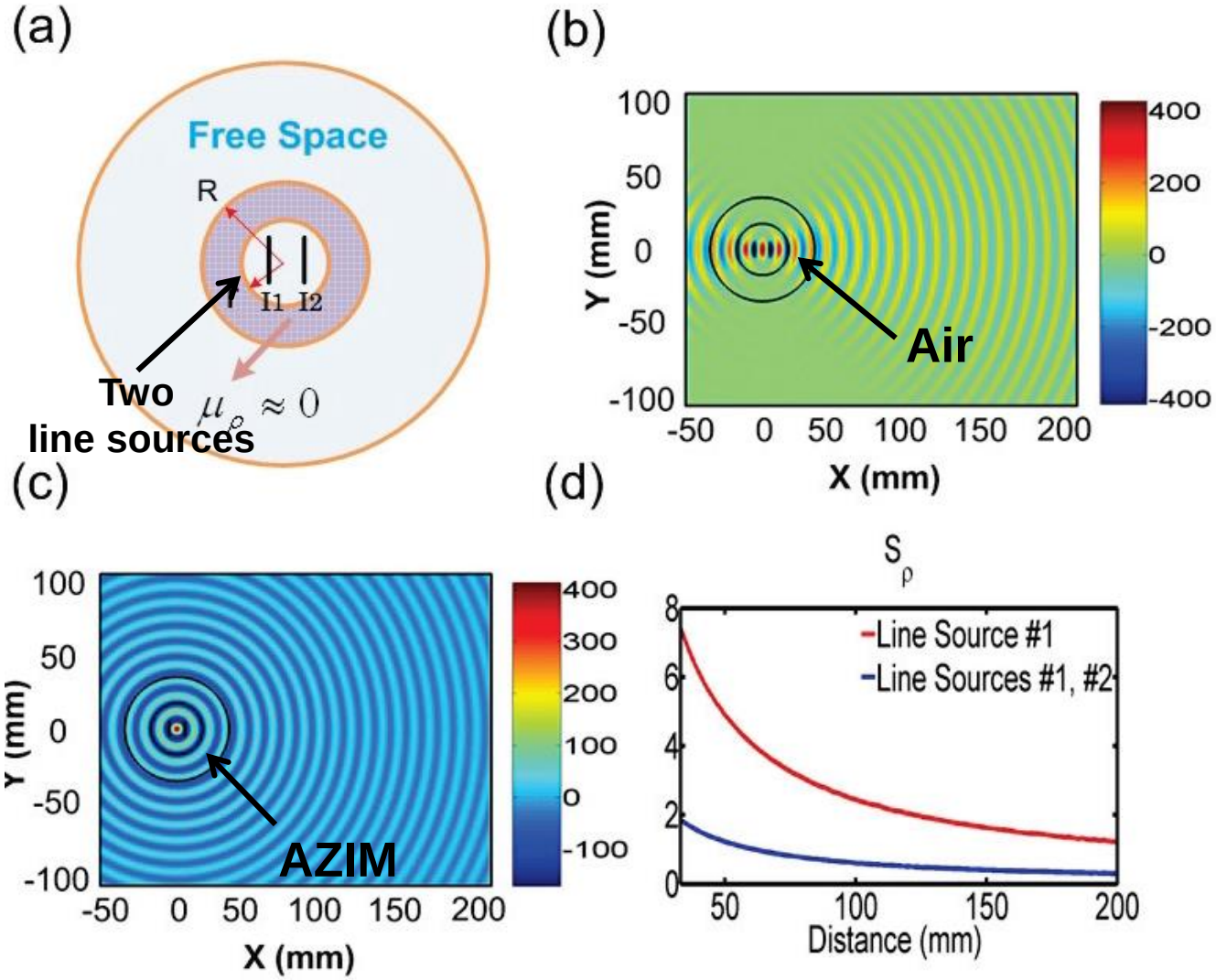
◆ Spatial Power Combination





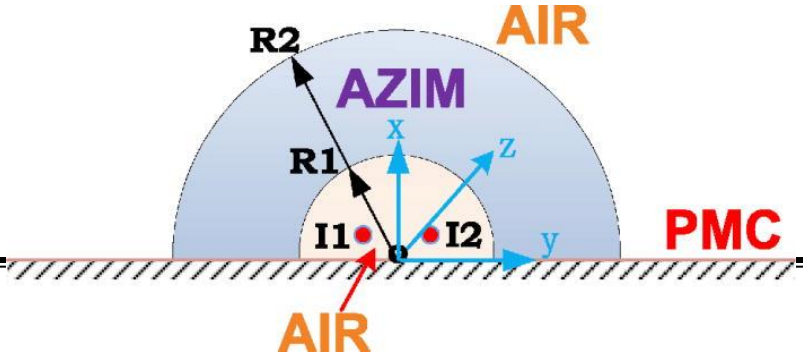
$$E_z^{(3)}(\vec{\rho}) = \frac{i}{4}\omega\mu_0[I_1 J_0(k_0\rho_1) + I_2 J_0(k_0\rho_2)]H_0^{(1)}(k_0\rho)$$

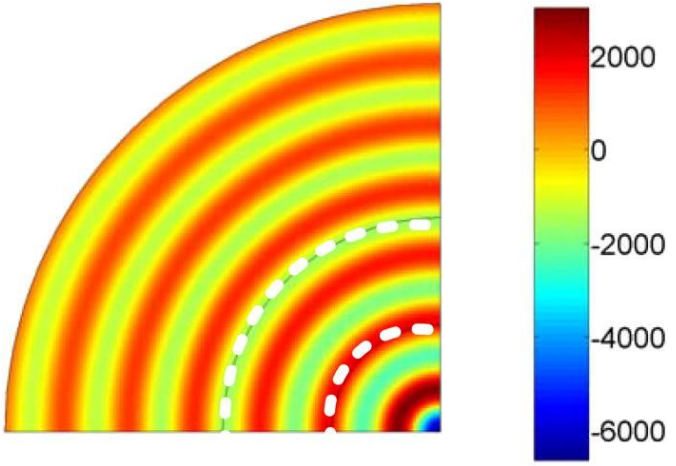
Cylindrical AZIM



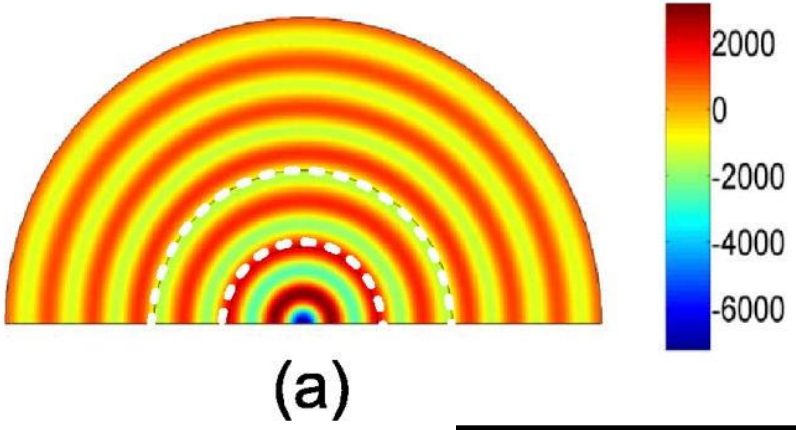
Q. Cheng, T. J. Cui, *et al*., Applied Physics Letters, vol. 101, 141902, 2012

Fan-Shaped Radiations

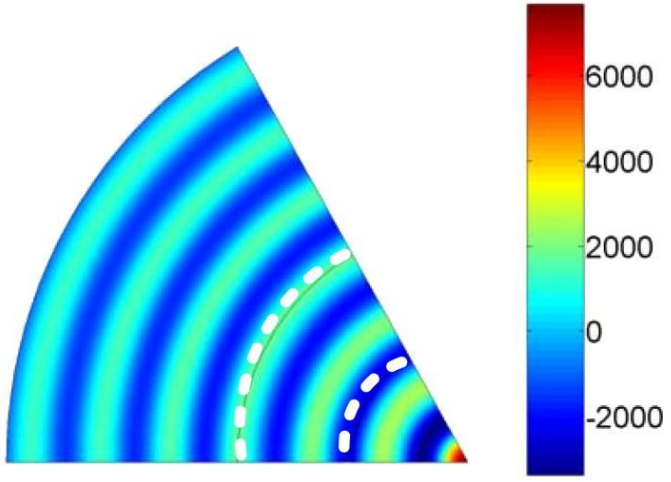




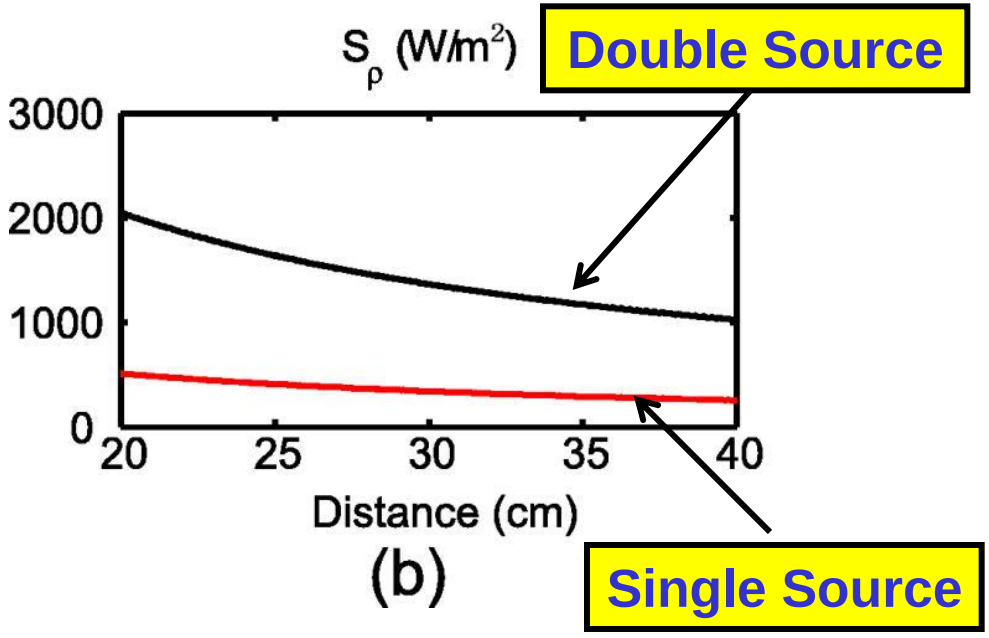
(a)



(a)



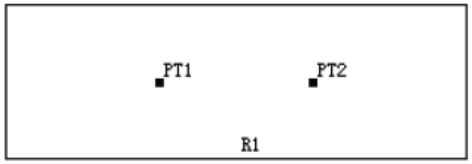
(b)



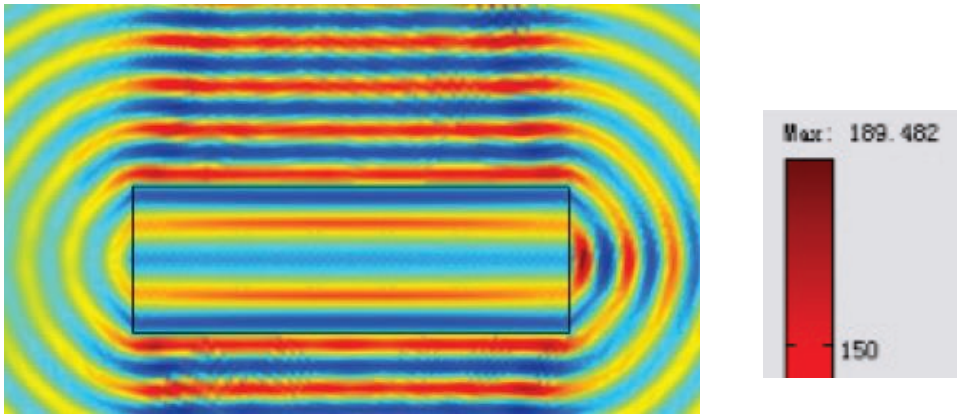
(b)

Spatial Power Combination

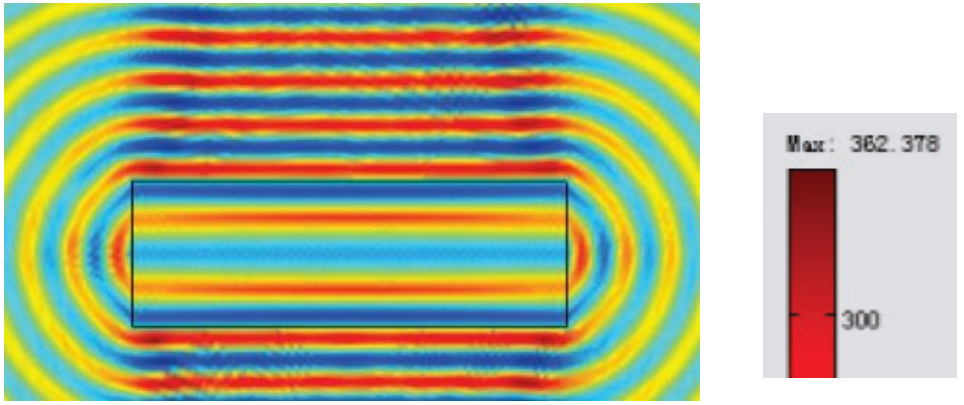
Directive Radiations



Single Source



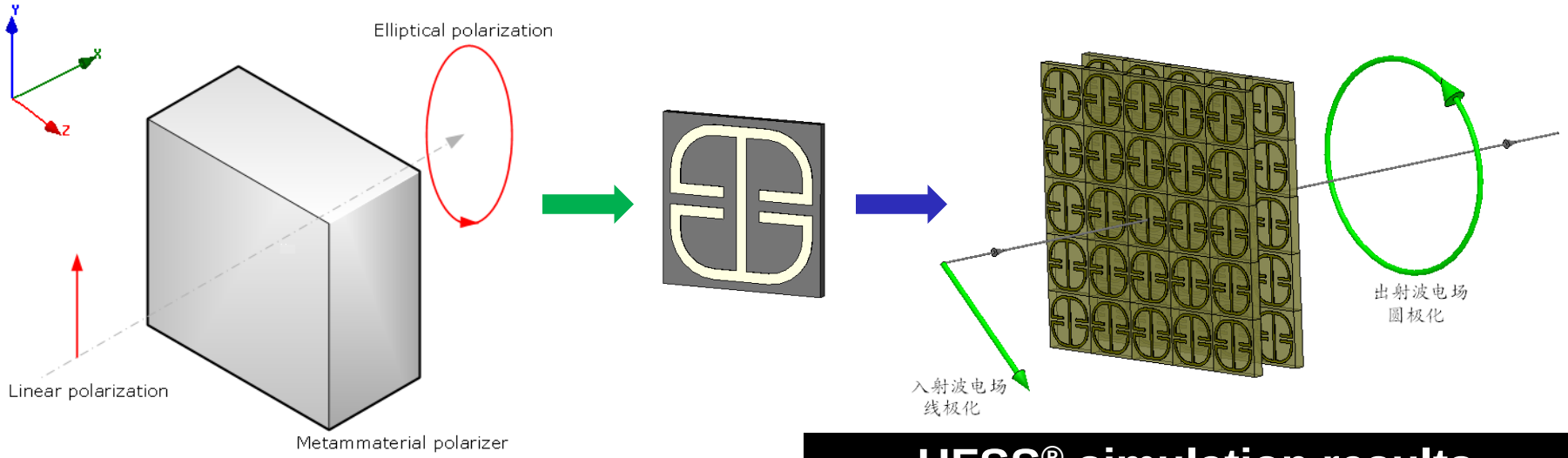
Double Sources



Metamaterial Lens Antennas

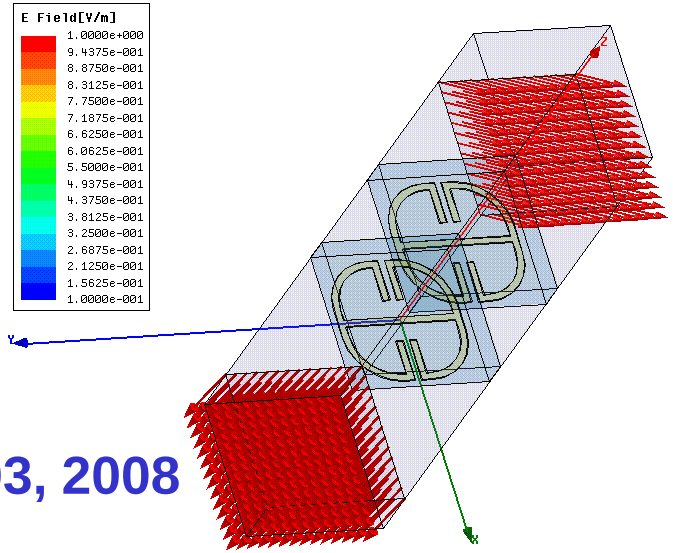
- **Slab Lens (Homogenous and Inhomogeneous);**
- **Curved Surface Lens (Luneburg Lens, Fisheye Lens, Fresnel Lens, etc.);**
- **Transformation Optics Lens;**
- **……**

Polarizer Lens



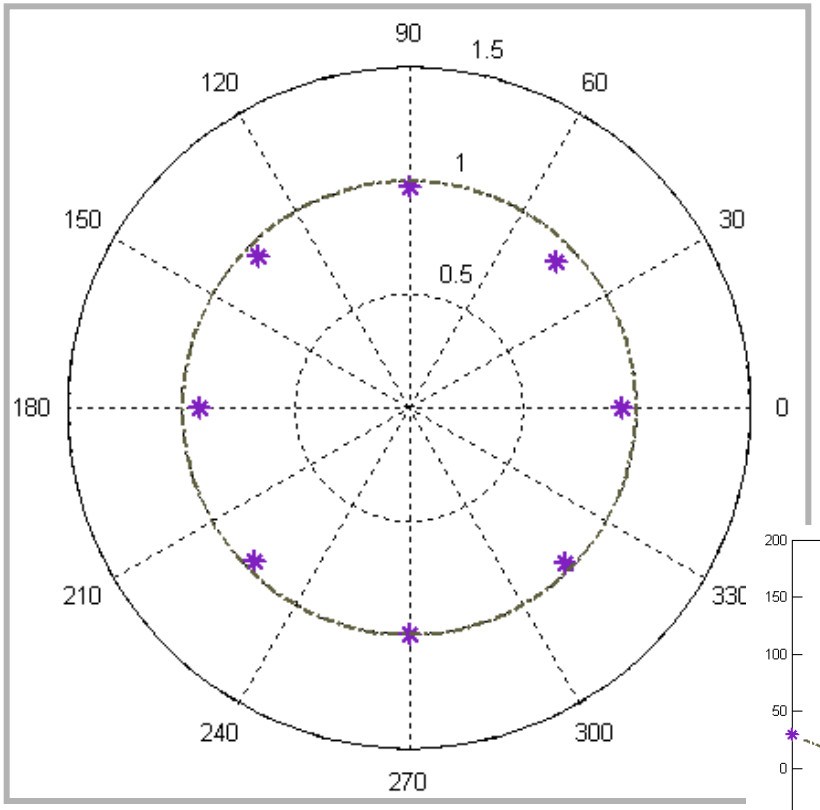
A polarizer lens can change the polarization status of antenna

HFSS® simulation results



J. Chin, M. Lu, T. J. Cui,
Applied Physics Letters, vol. 93, 251903, 2008

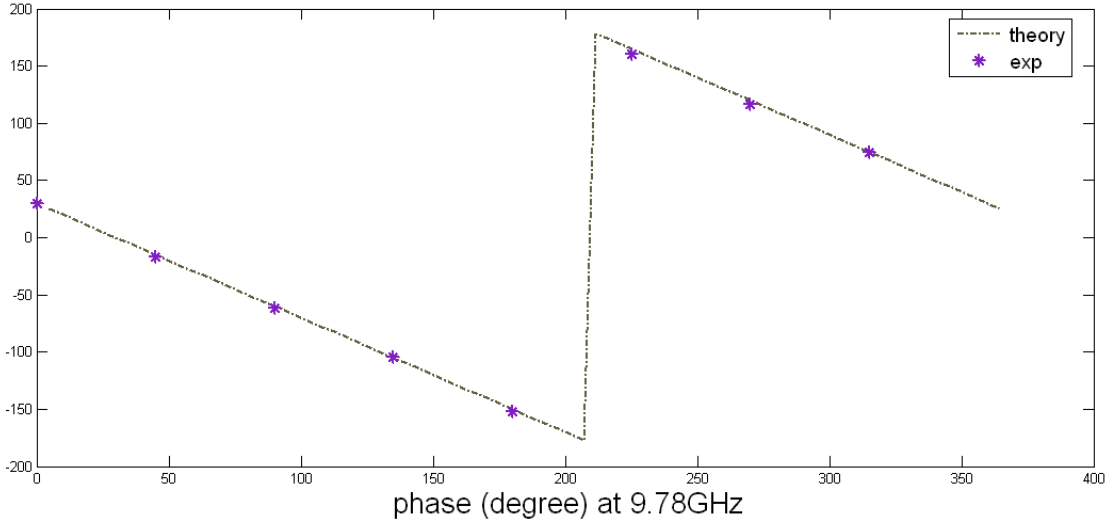
Polarizer Lens



2-Layer ELC Polarizer Lens

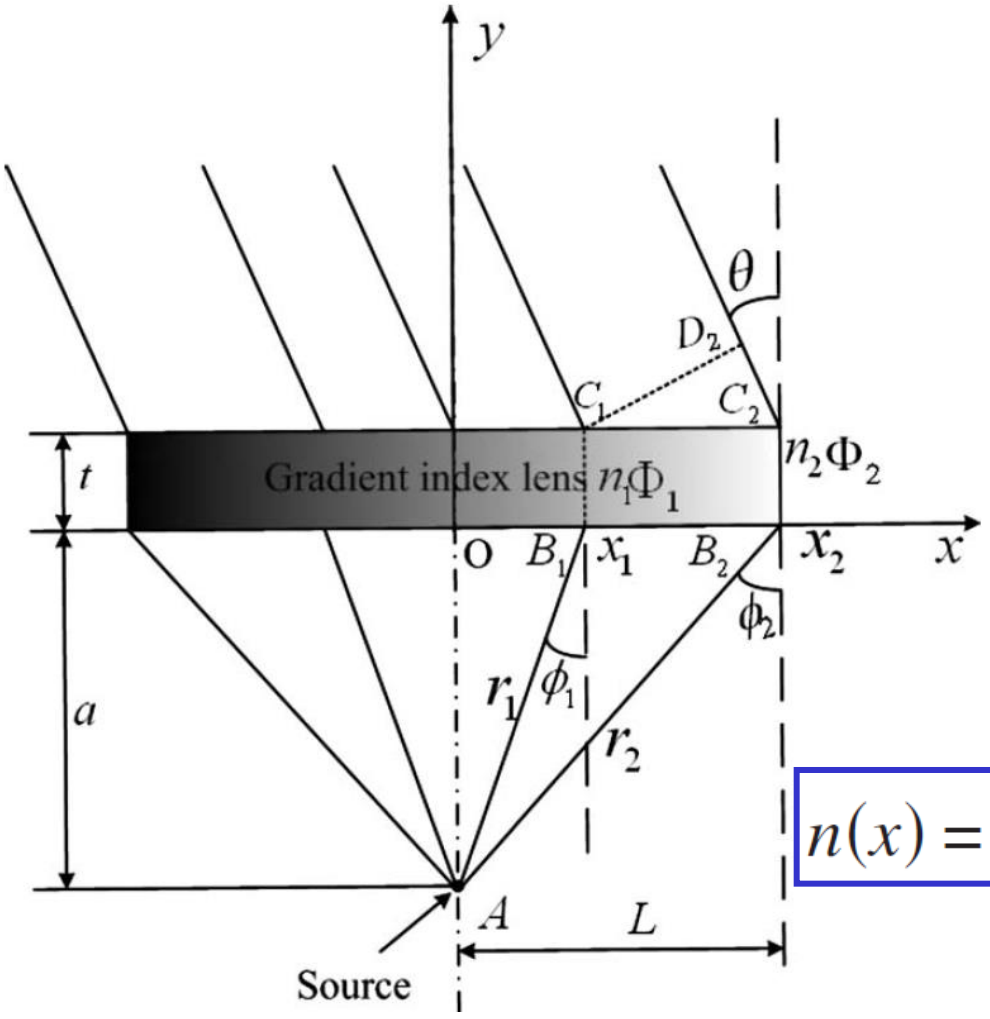
Measurement Results for Circular Polarization

Magnitude and phase of S21



The transmission loss is less than -1dB, good axis ratio.

2D Flat GRIN Lens



All optical paths from the source to the required wave front should have the same phase delay

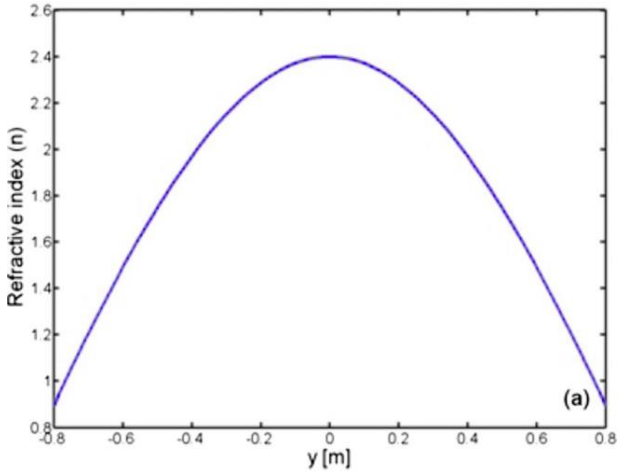
$$\sin\theta + \frac{x}{\sqrt{x^2 + a^2}} = -\frac{dn}{dx}t$$

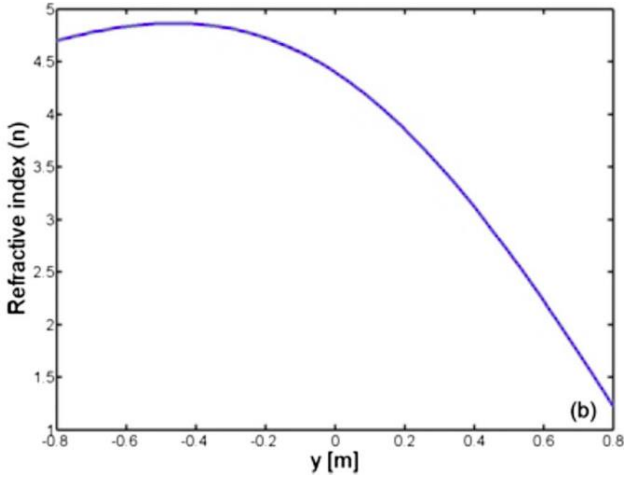
$$n(x) = n_0 - [x\sin\theta + (\sqrt{a^2 + x^2} - a)]/t$$

Gradient Index

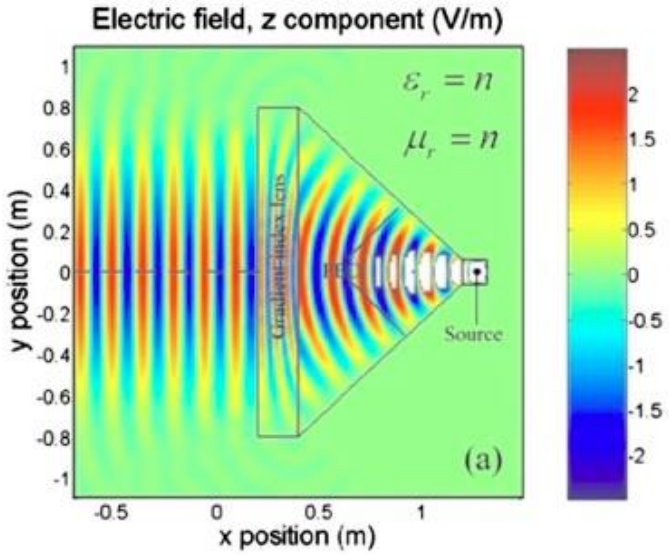
H. F. Ma, T. J. Cui, et al., Applied Physics Letters, vol. 95, 094107, 2009

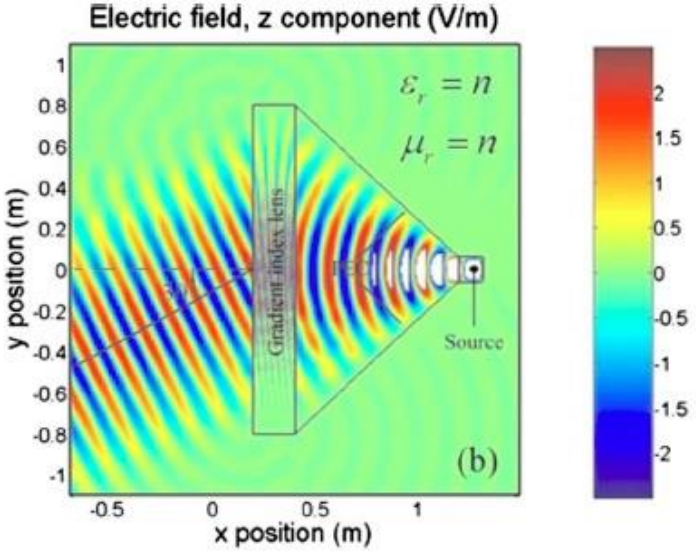
2D Flat GRIN Lens





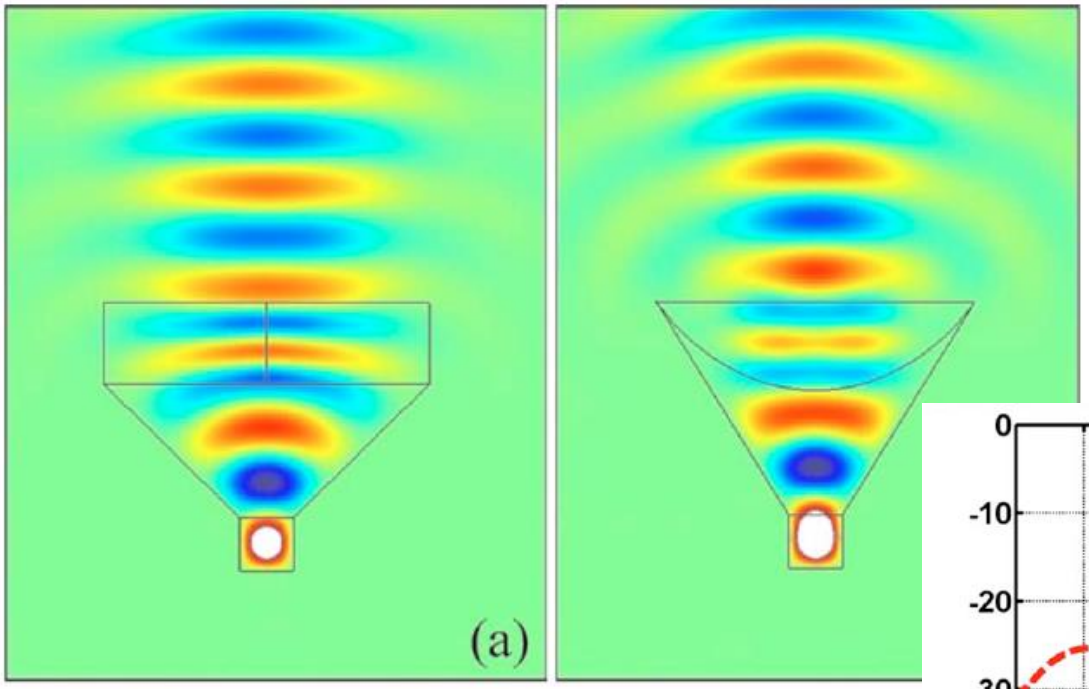
n distributions



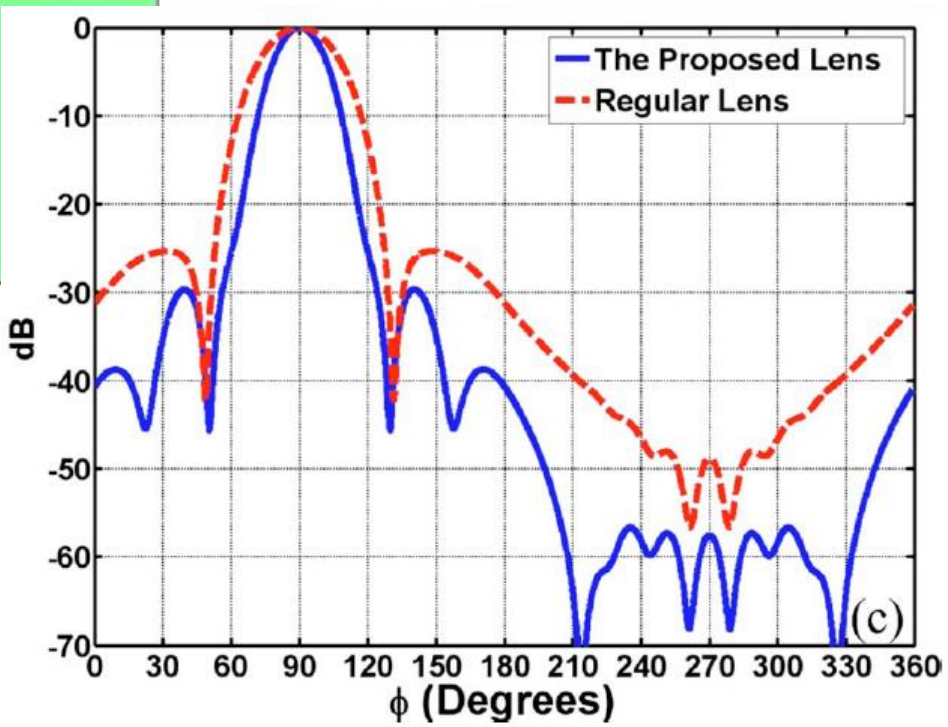


E distributions

2D Flat GRIN Lens

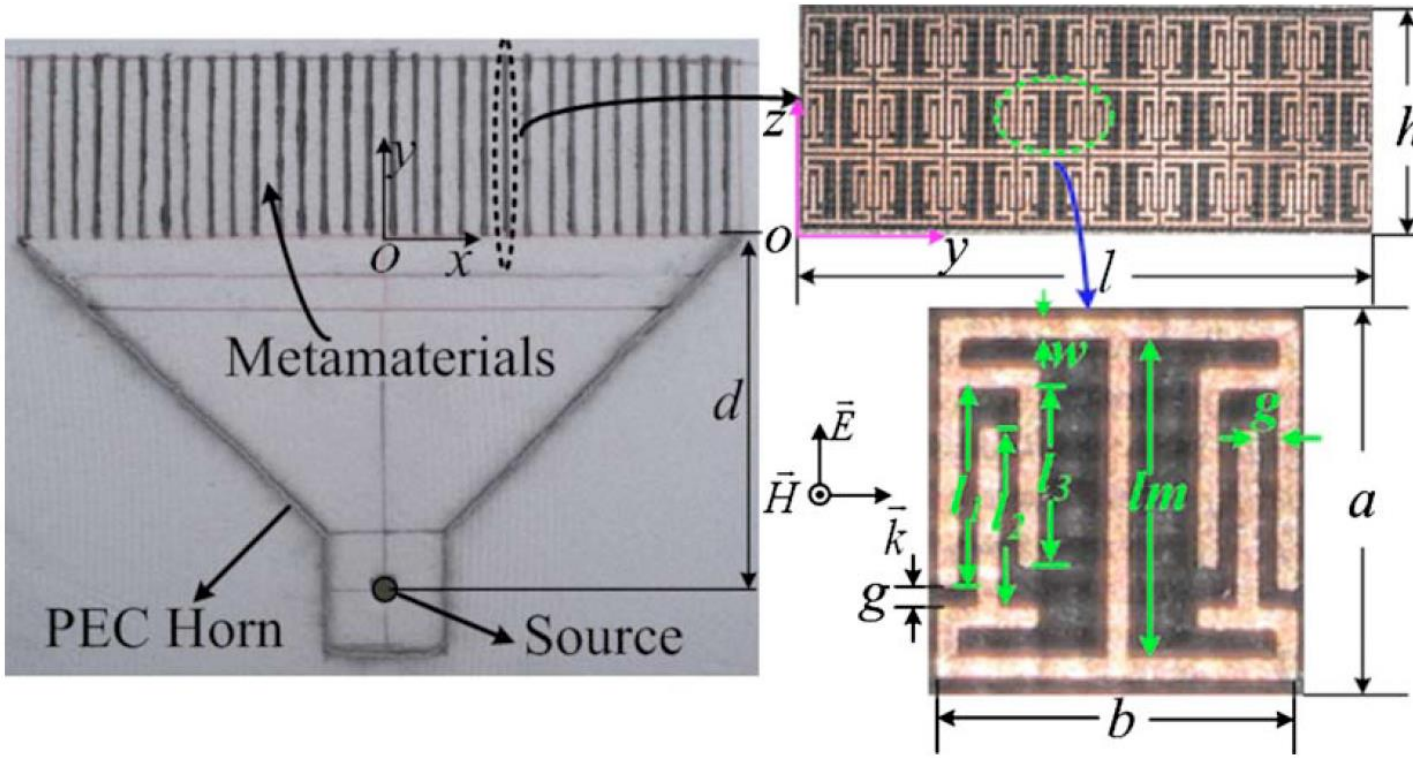


Comparison with Rotman Lens

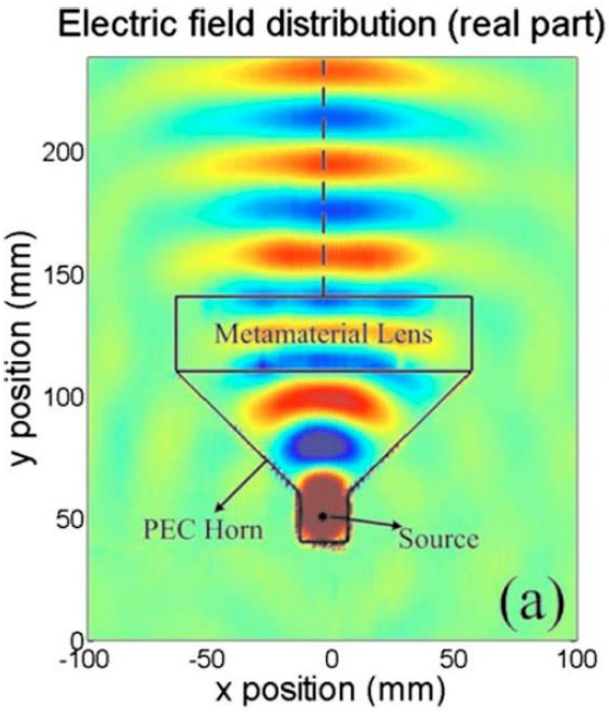


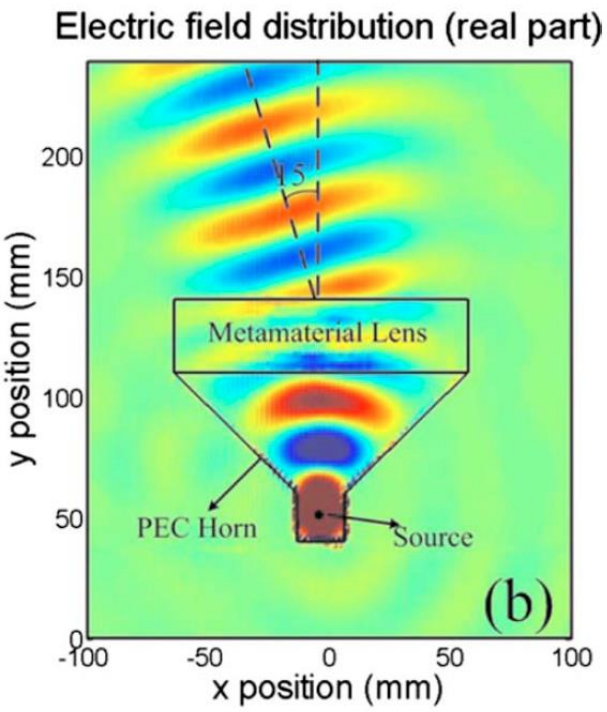
Both gain and sidelobes have been improved using the GRIN lens, breaking the constraint of antennas.

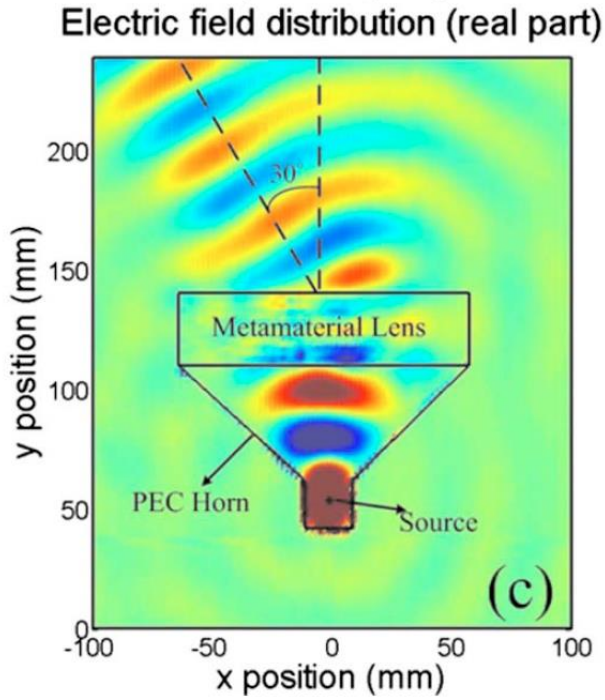
2D Flat GRIN Lens

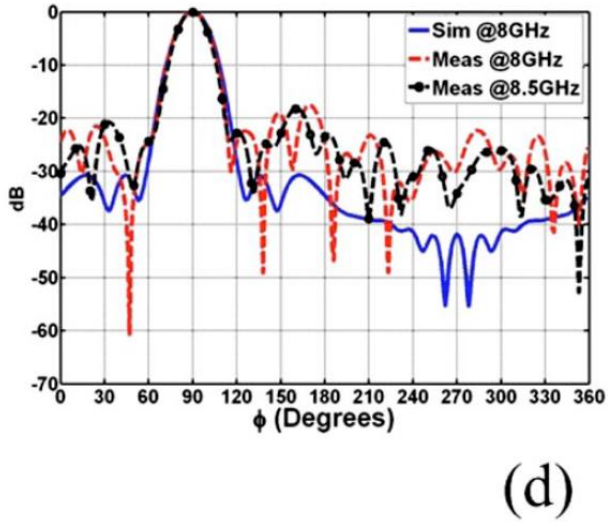


- **Both electrical and magnetic responses**
- **Impedance matching**
- **Aperture: 12cm, 8 GHz**



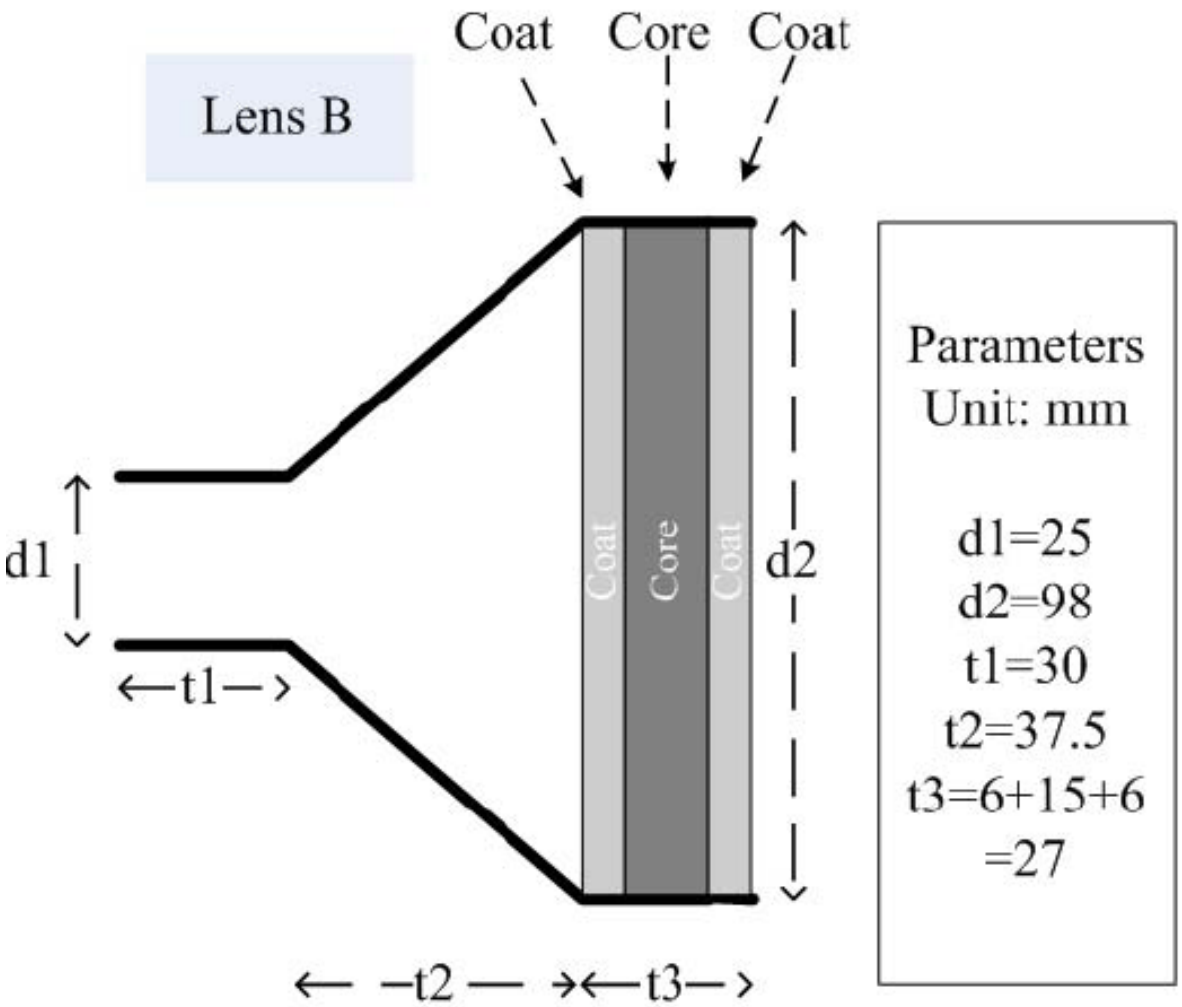






Measurement results

3D Flat Lens Antenna

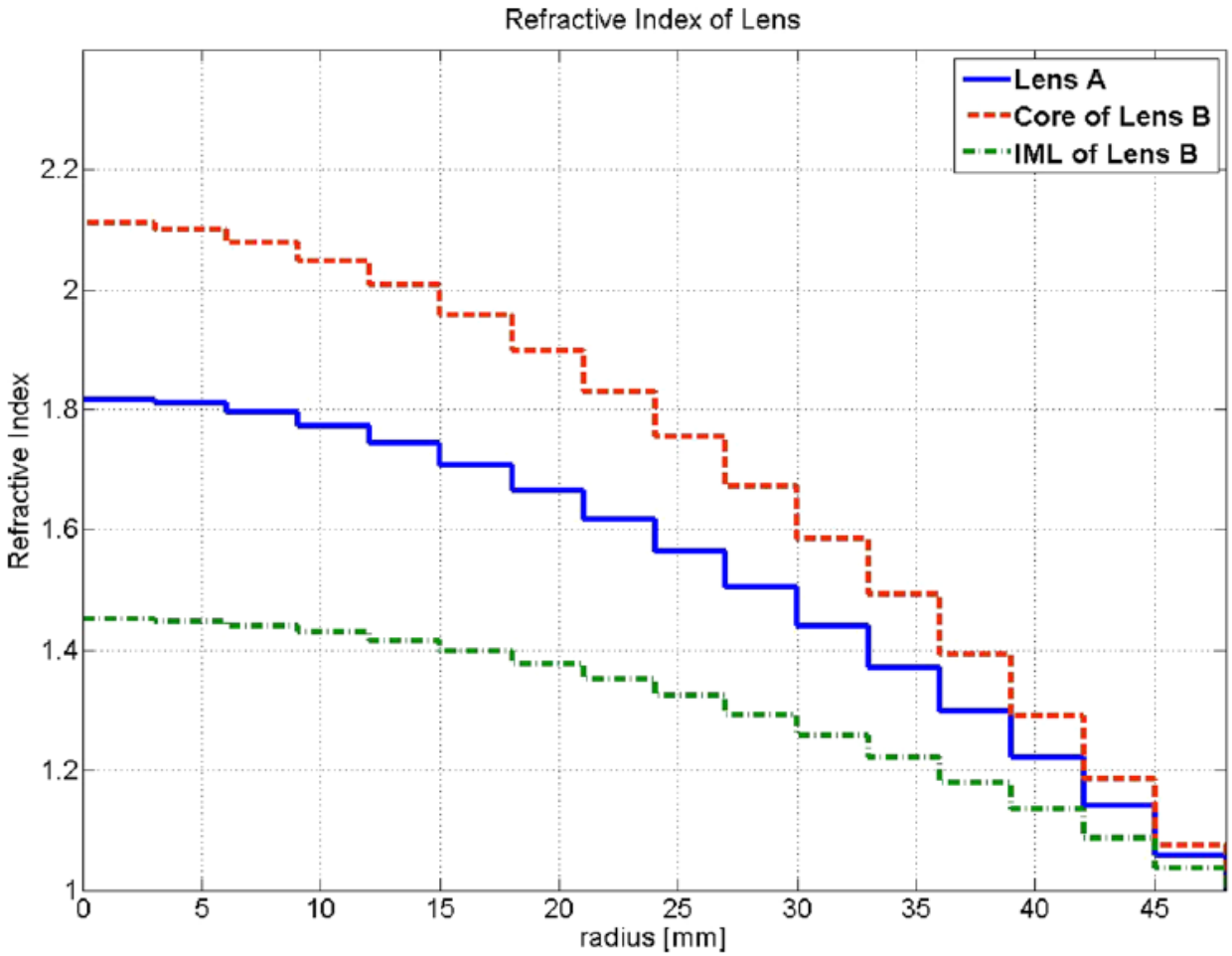


- **Coat-Core-Coat Sandwich Structure**
- **Core: Gradient Index Lens**
- **Coat: Impedance Matching Layer**

X. Chen, H. F. Ma, T. J. Cui, Journal of Applied Physics, vol. 110, 044904, 2011

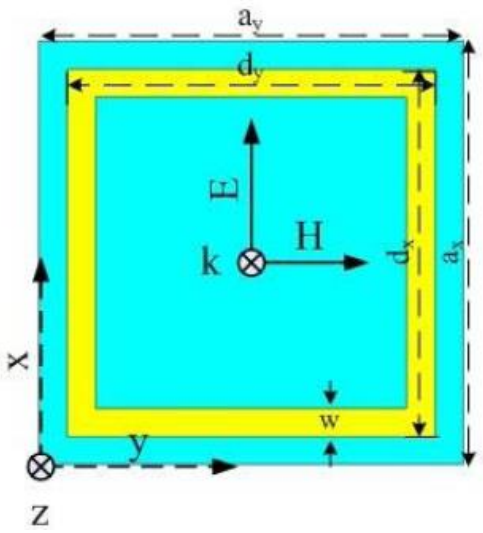
3D Flat Lens Antenna

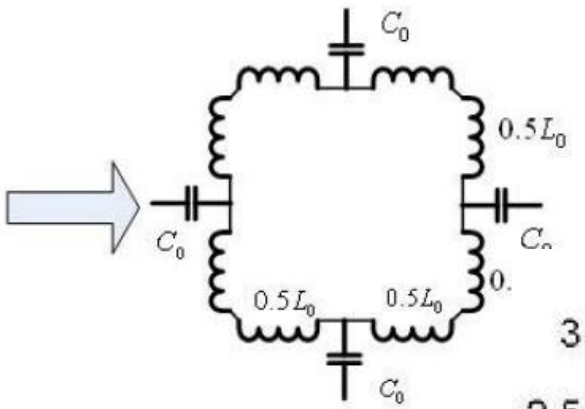
- **Requirements to n distributions**



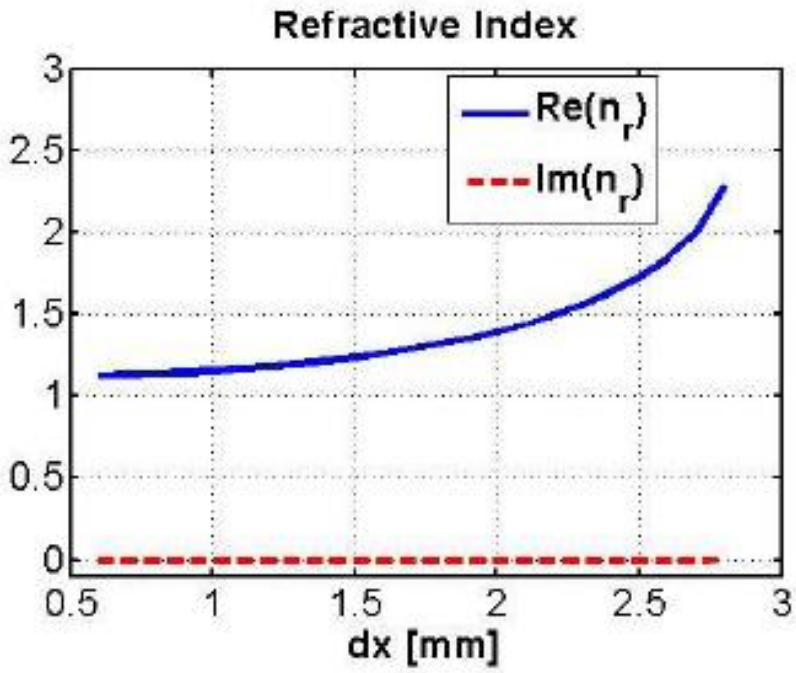
3D Flat Lens Antenna

◆Design of unit cells





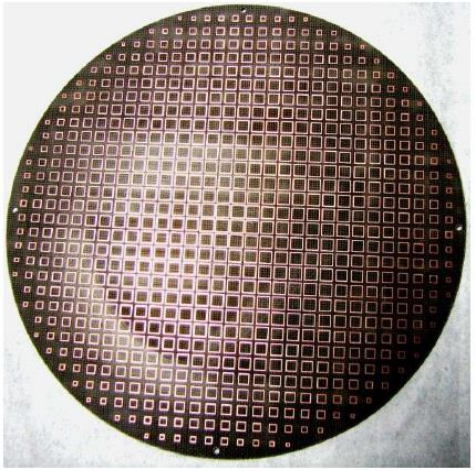
Square-Ring Unit Cell

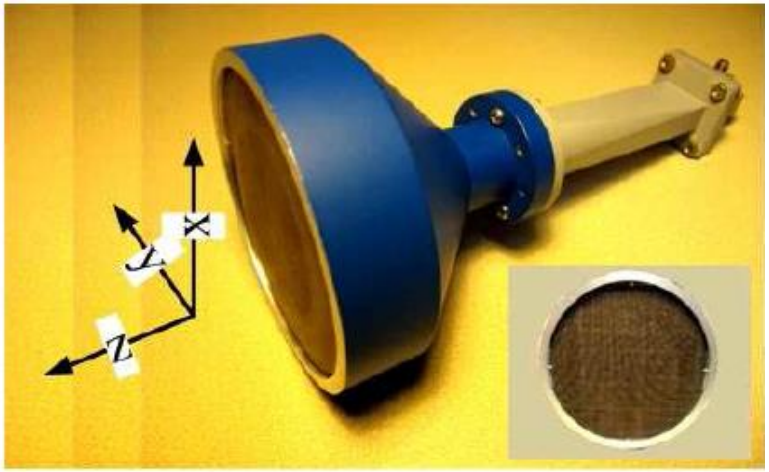


Retrieved Distribution of Refractive Index n

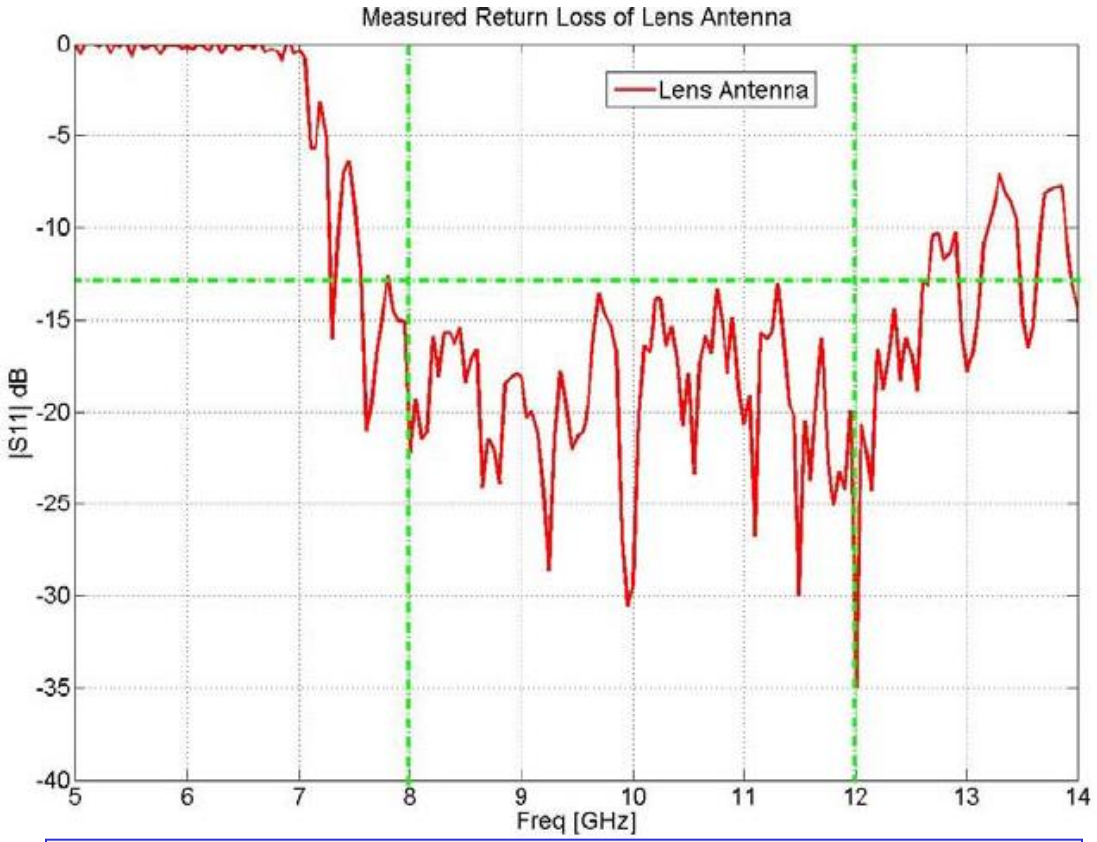
3D Flat Lens Antenna

◆Fabricated 3D Flat Lens



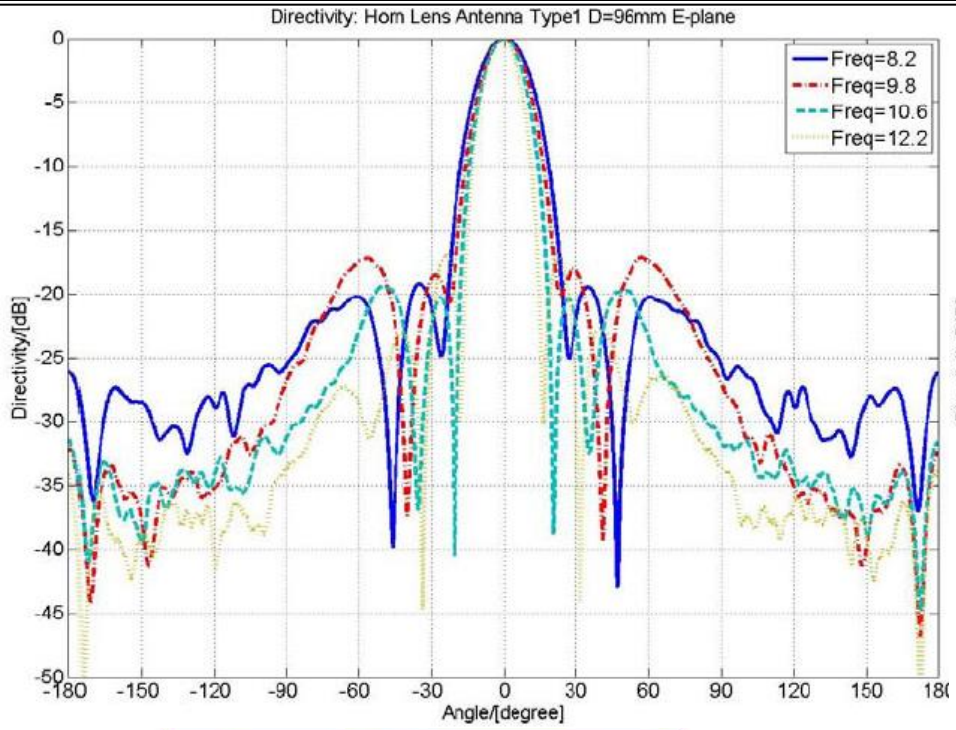


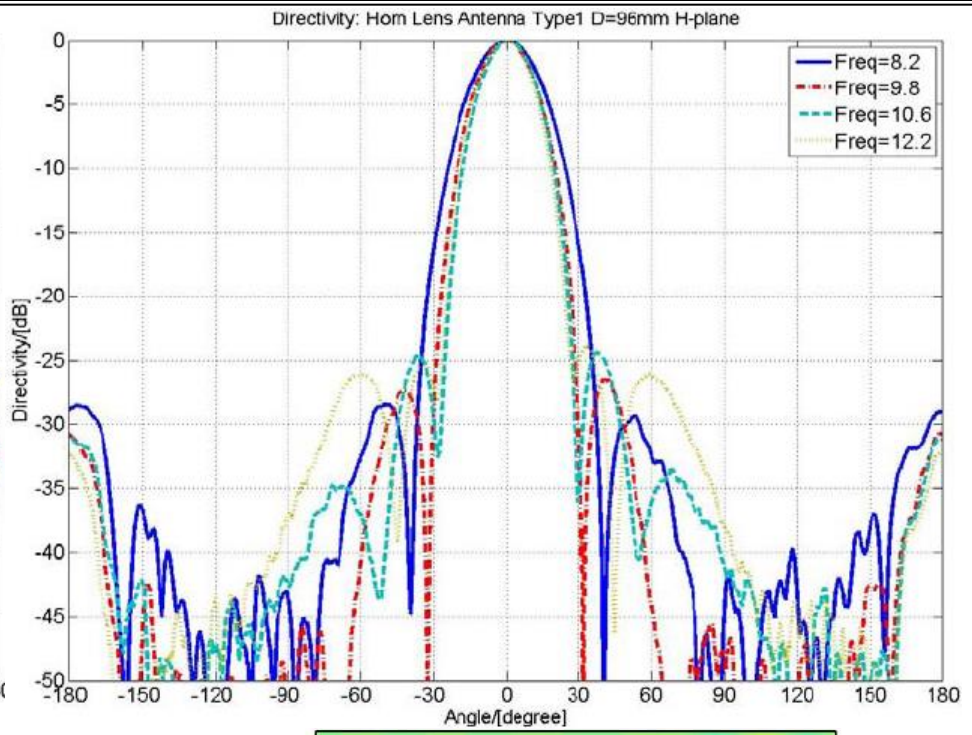
Aperture Size 9.6cm

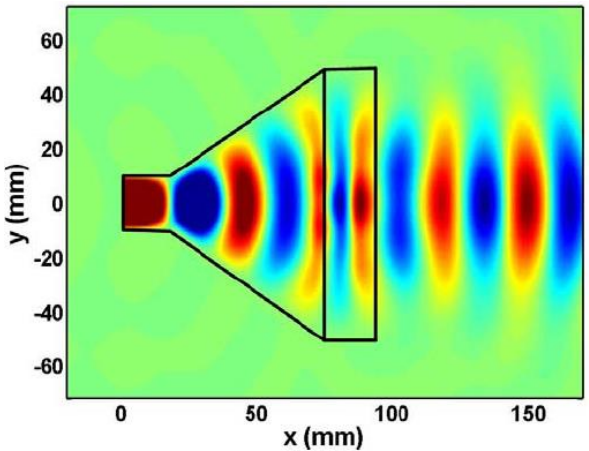


◆ Measured Return Loss: Below -14dB from 8 to 12 GHz

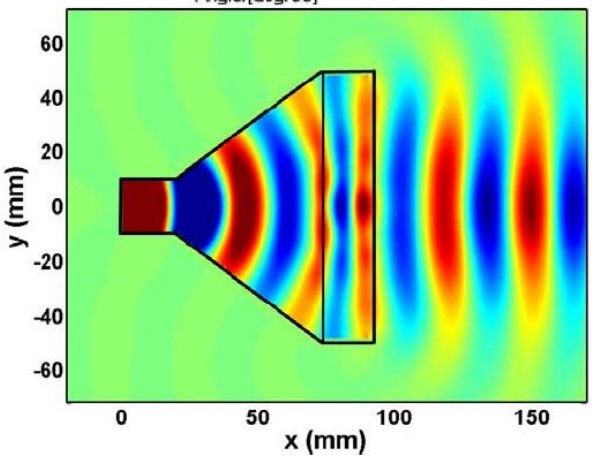
3D Flat Lens Antenna







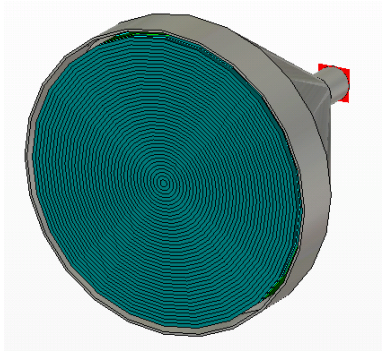
Measured Gain 23 dBi @12 GHz 6dBi higher than the horn

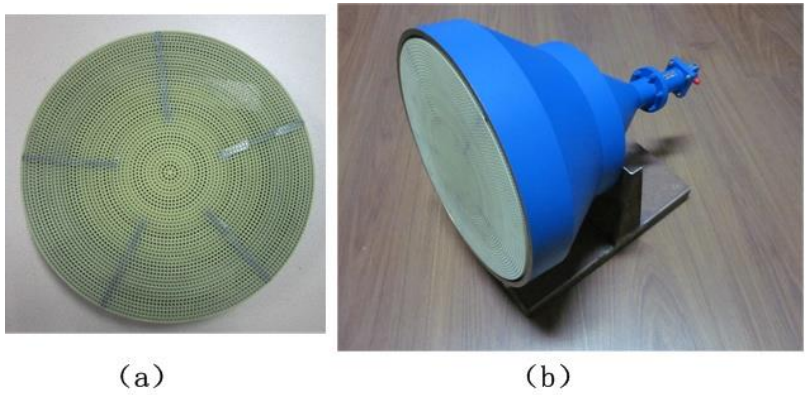


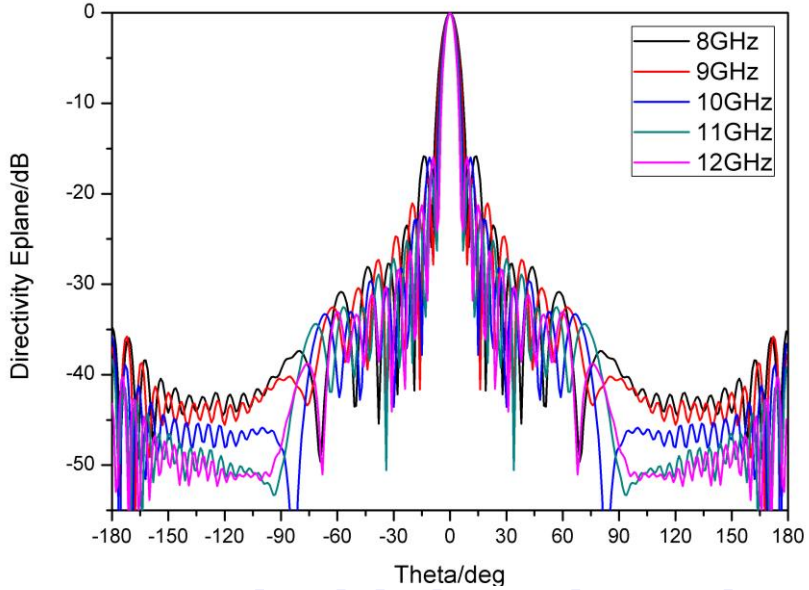
3D Flat Lens Antenna

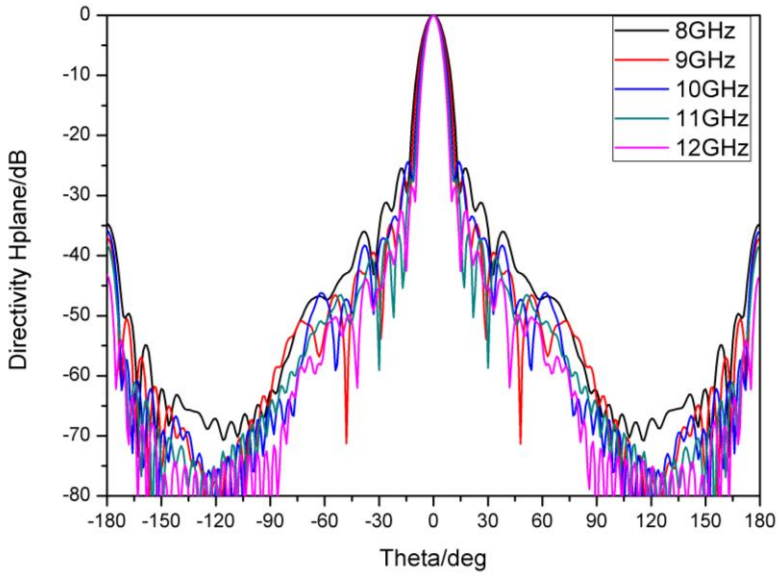
Aperture: 25cm
30dB @12GHz

Ray tracing has been used to design the lens





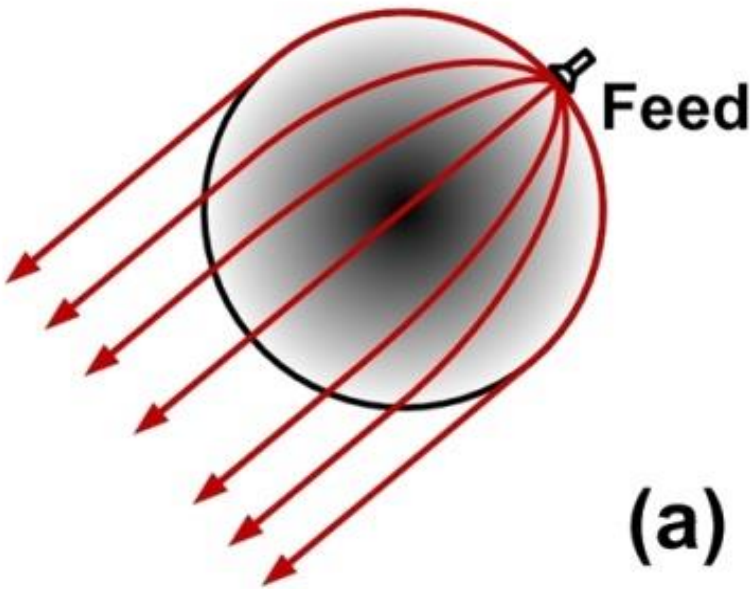




5dB higher than the Rotman dielectric lens

X. Y. Zhou, T. J. Cui, et al. Science China Information Sciences, 56, 12, 2013

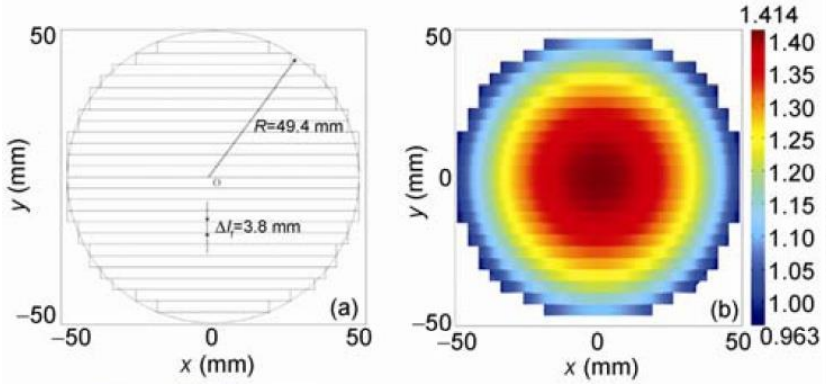
Luneburg Lens

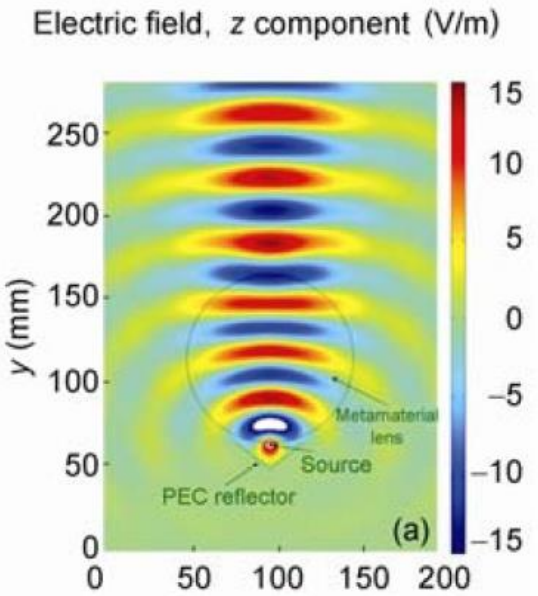


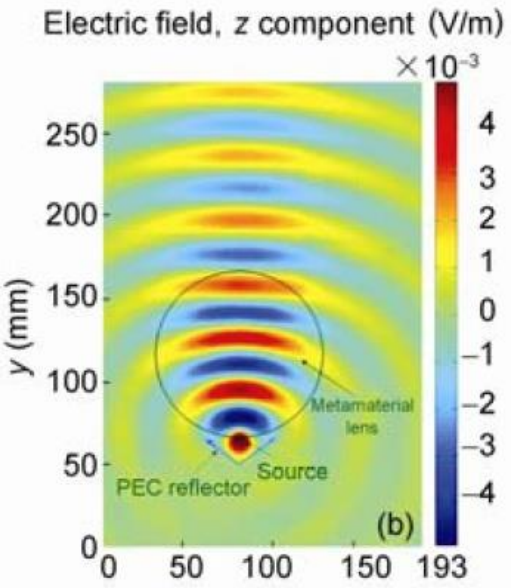
$$n = \sqrt{2 - (r/R)^2}$$

- Expensive
- Discrete Multilayers
- Impedance Mismatch among Layers

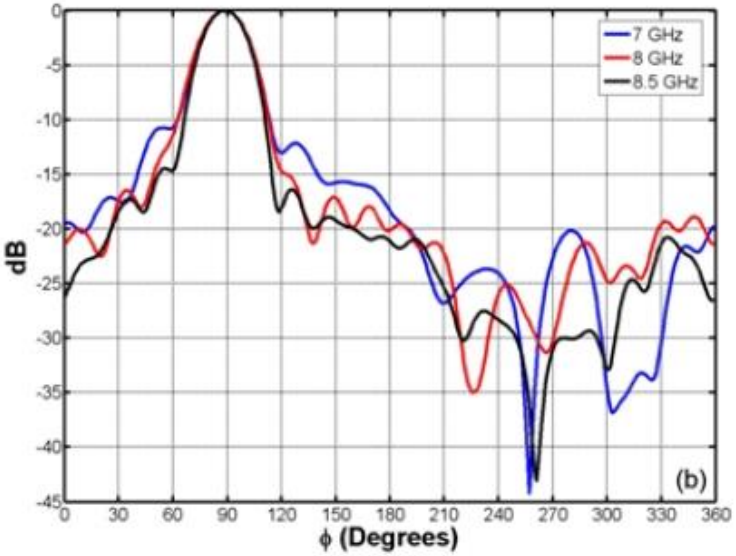
2D Luneburg Lens







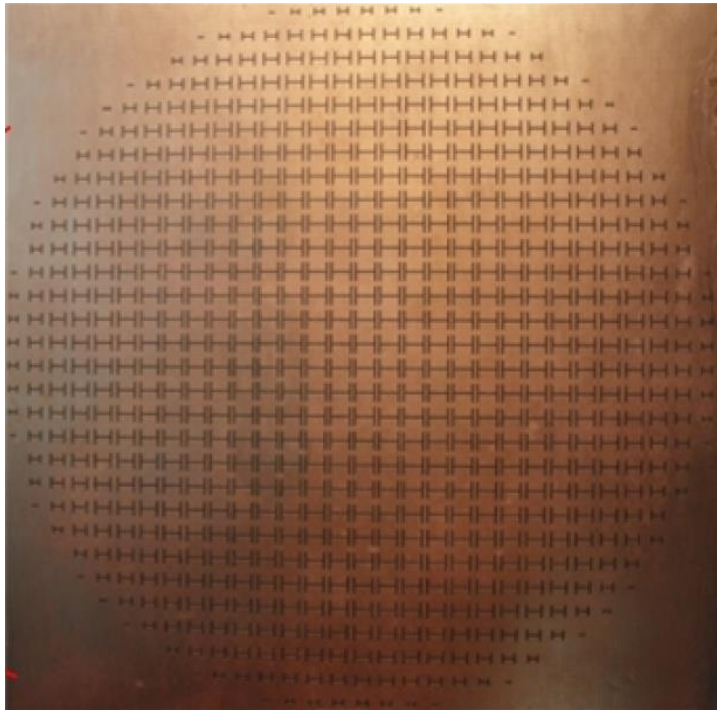
Size: R=5cm

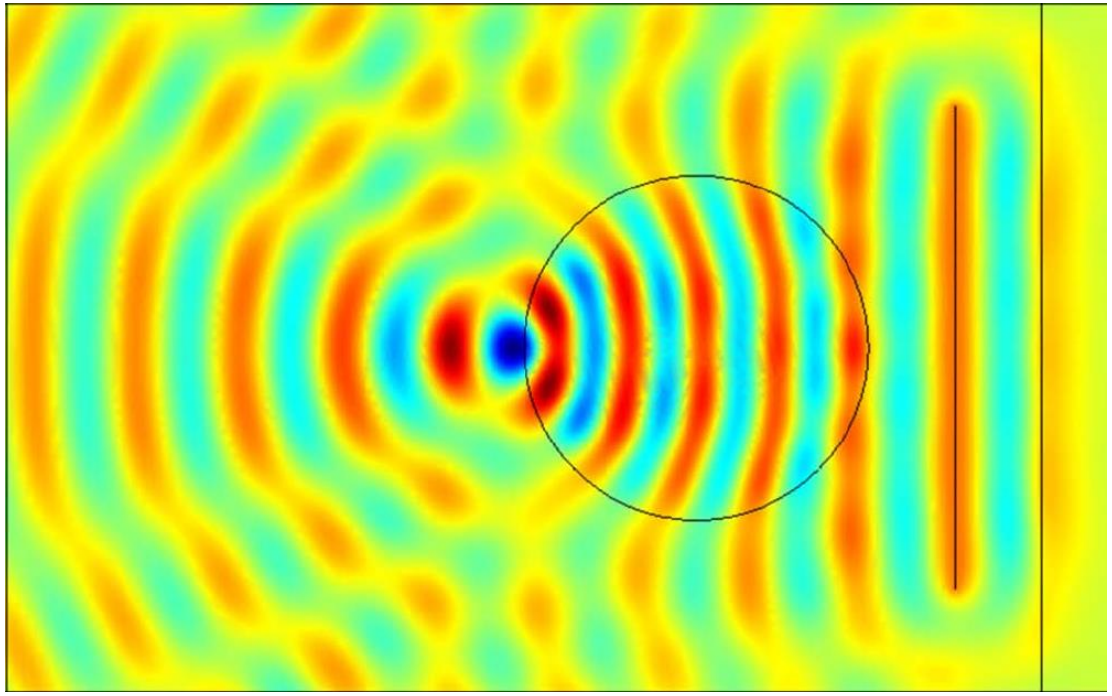


H. F. Ma, T. J. Cui, et. al.

***Chinese Science Bulletin, vol. 55*, pp. 2066-2070, 2010**

Complementary Planar Luneburg Lens

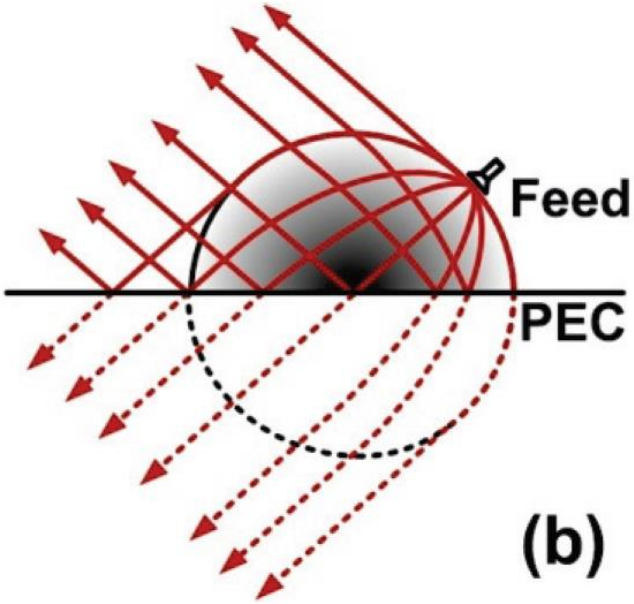


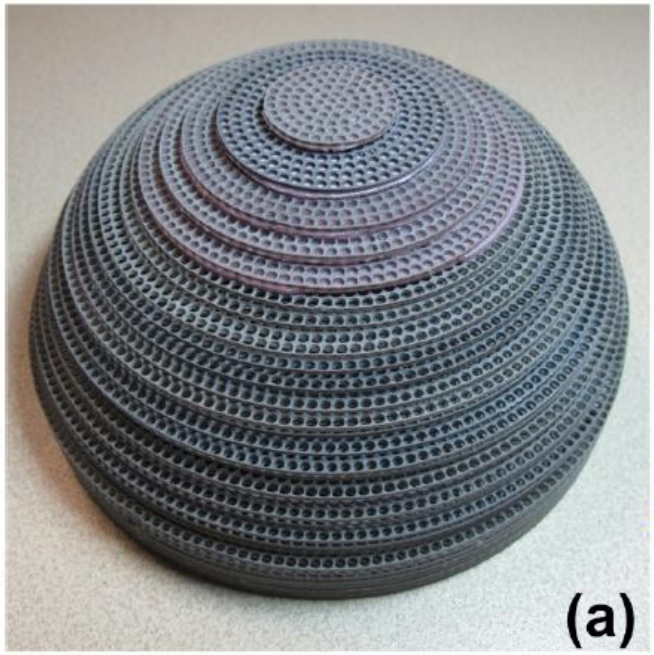


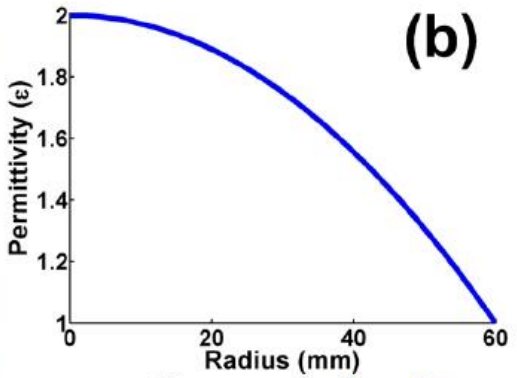
Complimentary I-shaped unit cells are used

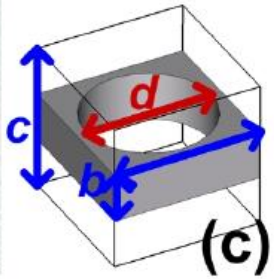
Q. Cheng, T. J. Cui, et. al., Applied Physics Letters, vol. 95, 181901, 2009

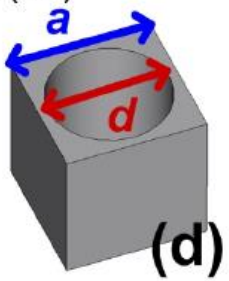
3D Half Luneburg Lens







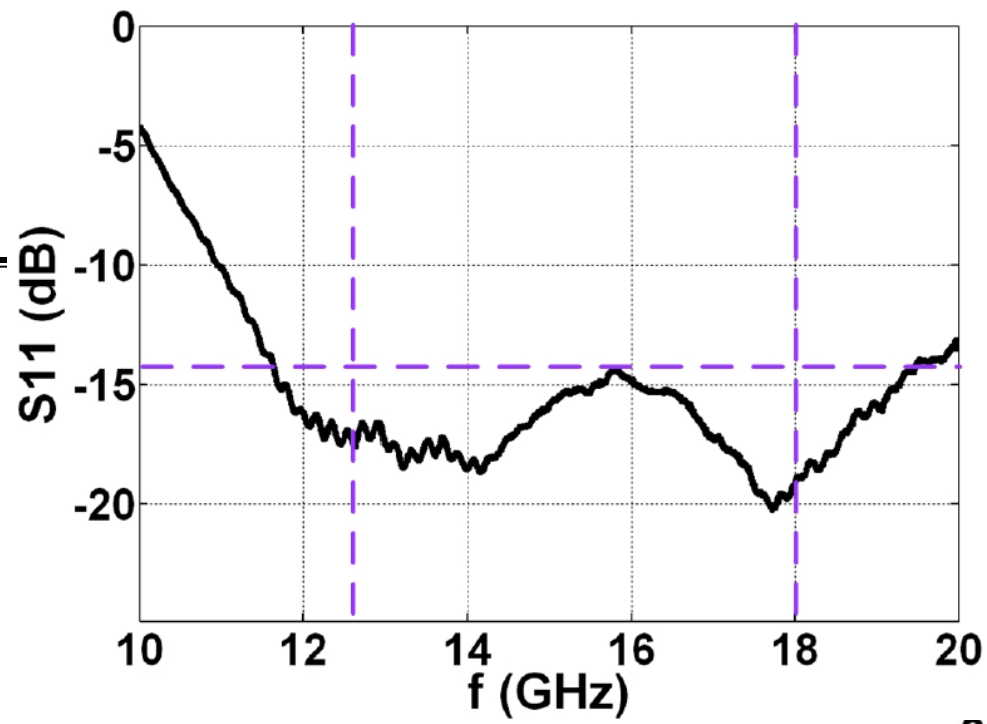


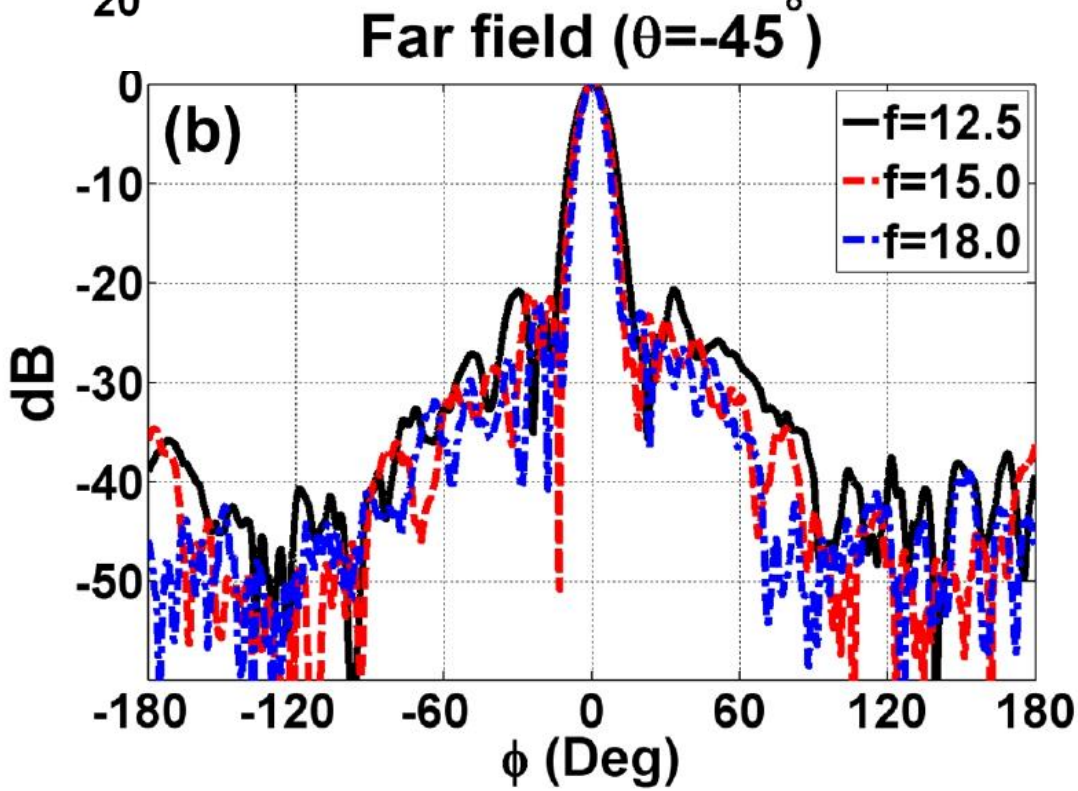


H. F. Ma, T. J. Cui, et al. IEEE Transactions on Antennas and propagation, vol. 61, pp. 2561-2569, 2012

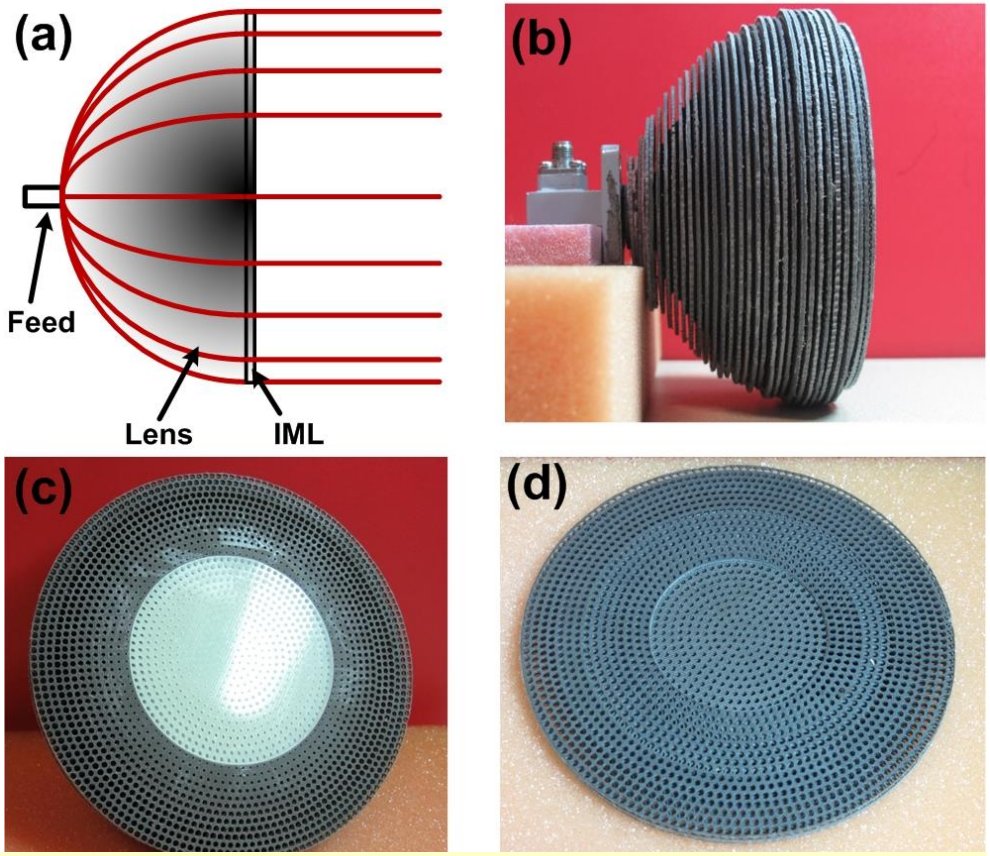
- Dielectric with hole
- Broadband
- Easy fabrication; Cheap
- Good impedance matching among layers

3D Half Luneburg Lens

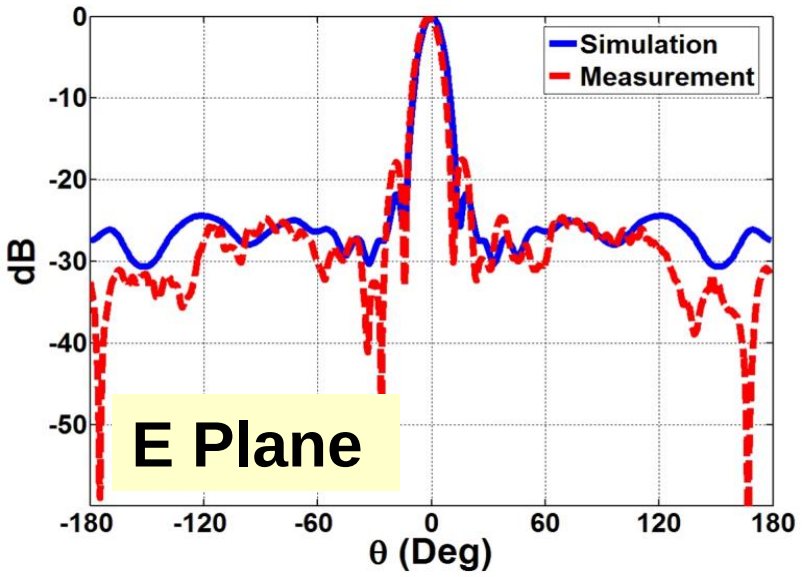


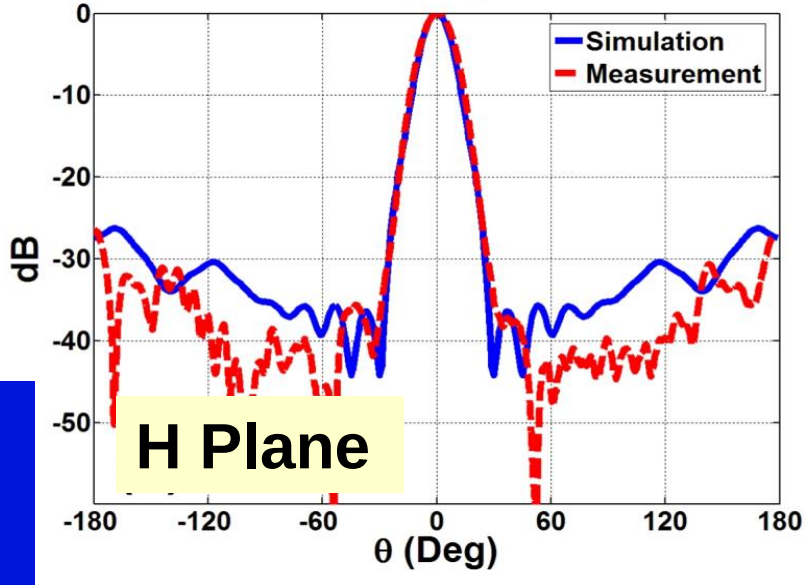


Maxwell Fisheye Lens



Radius: 6cm; Frequency: 12-18GHz





H. F. Ma, T. J. Cui, et al.
IEEE Transactions on Antennas and propagation, vol. 61, pp. 2561-2569, 2012

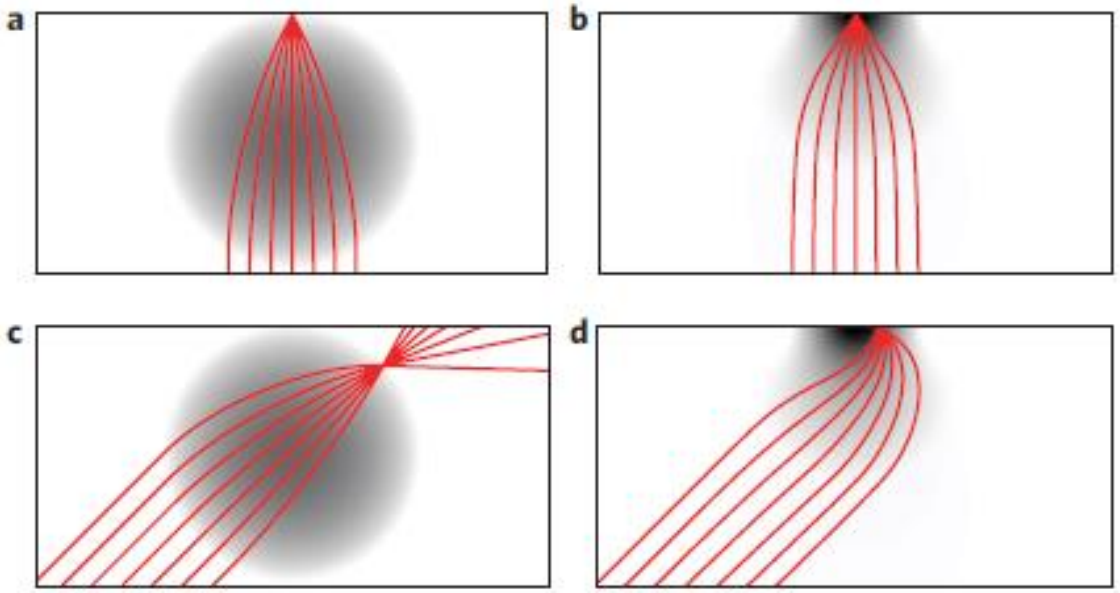
3D Transformation Optics Lens

Traditional Luneburg Lens

- **Advantages:**
  - **High directivity;**
  - **Low sidelobes;**
  - **Multi-beam radiation; Beam steering**
- **Disadvantages:**
  - **Spherical focal surface**
  - **Inconvenient for array feeding**

3D Transformation Optics Lens

◆2D Flattened Luneburg Lens



- ◆ Optical Transformation
- ◆ Part of spherical surface is transformed to a planar surface
- ◆ High gain
- ◆ Low sidelobes
- ◆ Beam steering
- ◆ Flat focal plane
- ◆ Easy for array feeding

Schurig, *New J. Phys.* **19**, 115034, 2008

Kundtz & Smith, *Nat. Mater.* **9**, 129, 2010

nature COMMUNICATIONS

ARTICLE

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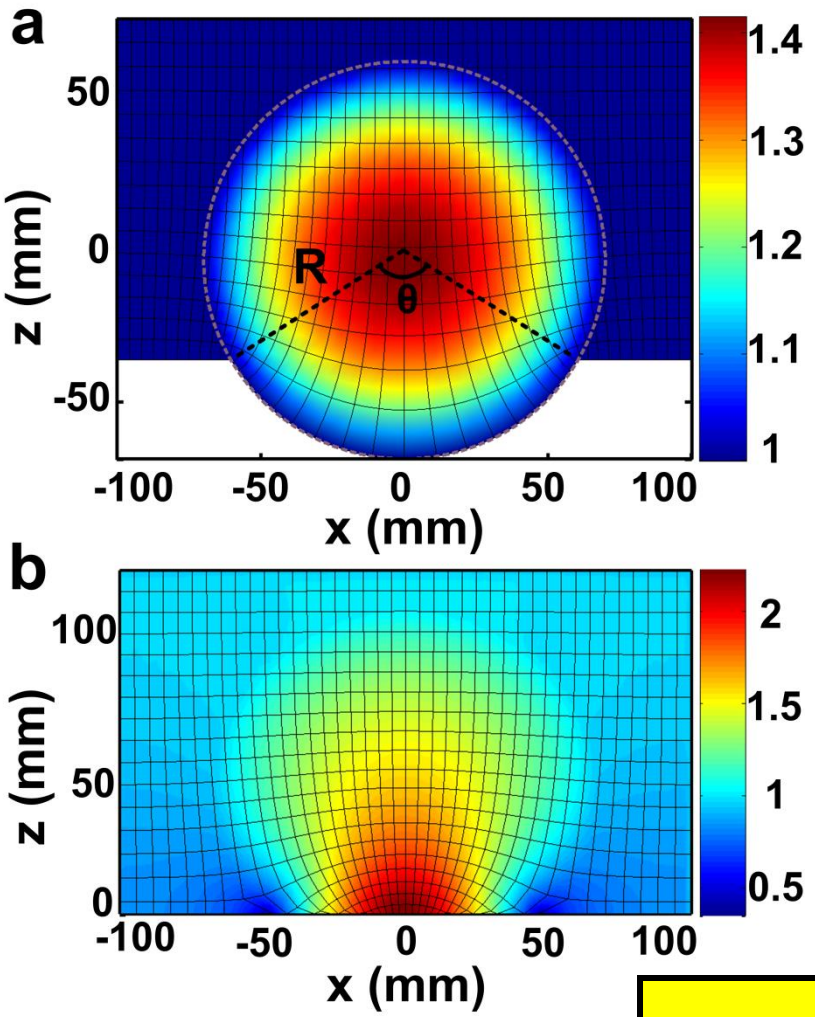
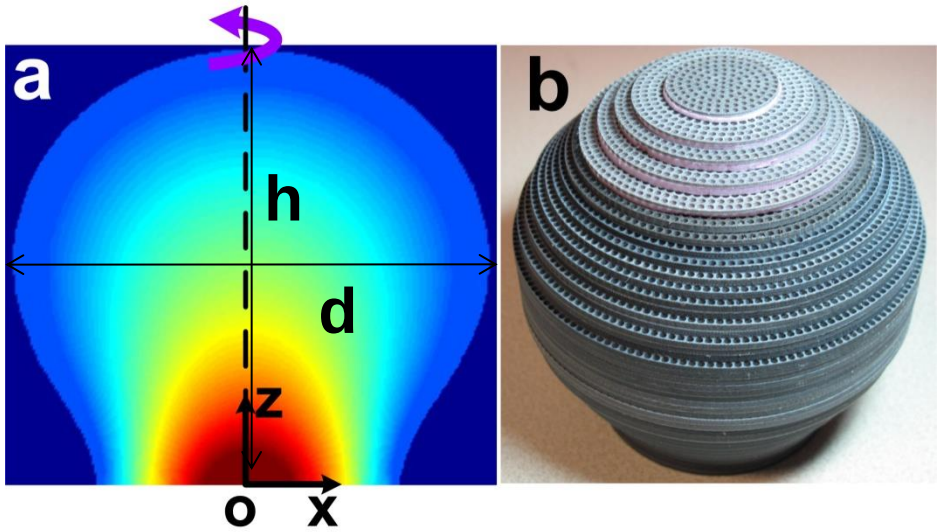
DOI: 10.1038/ncomms1126

Three-dimensional broadband and broad-angle transformation-optics lens

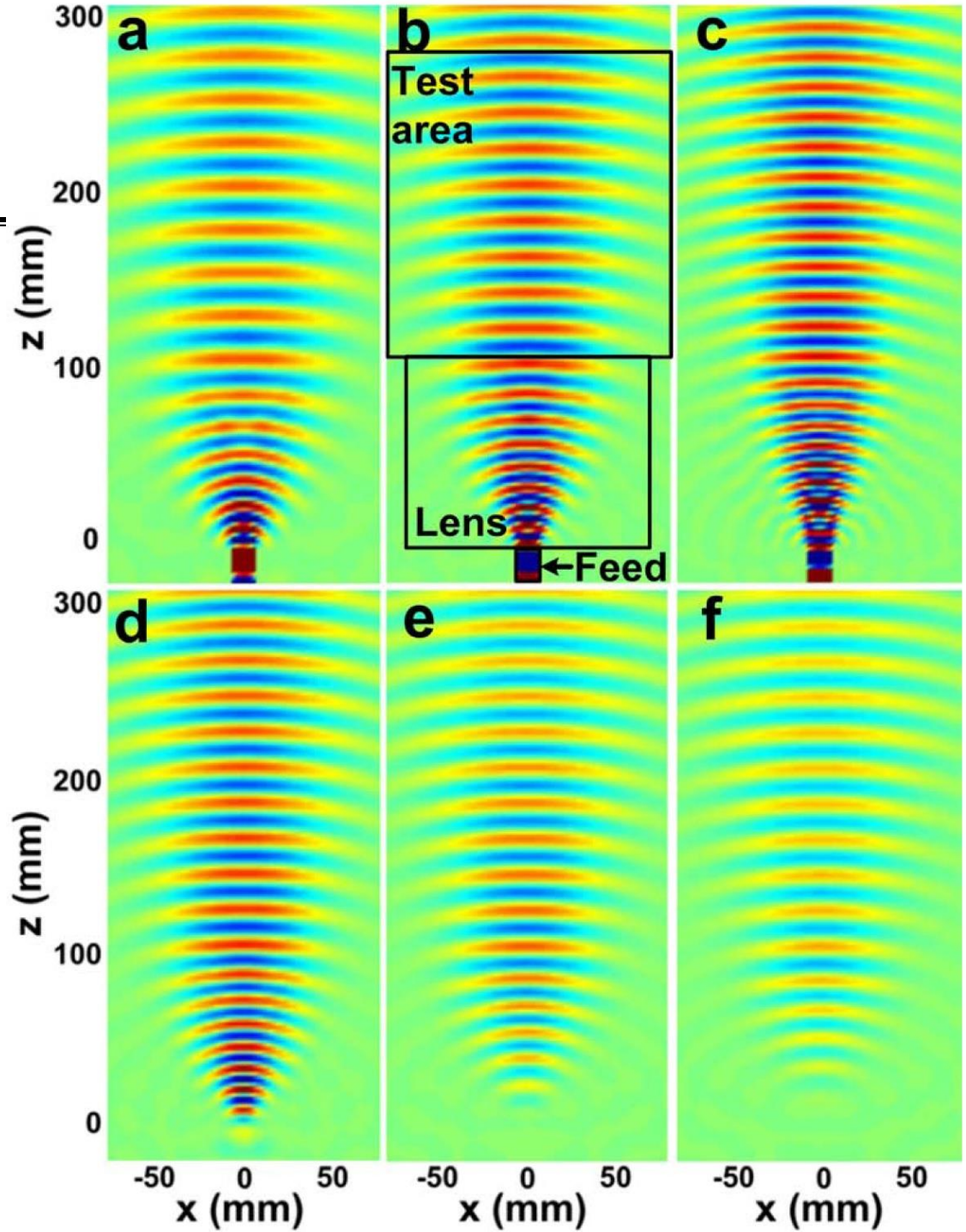
Hui Feng Ma & Tie Jun Cui

3D Transformation Optics Lens

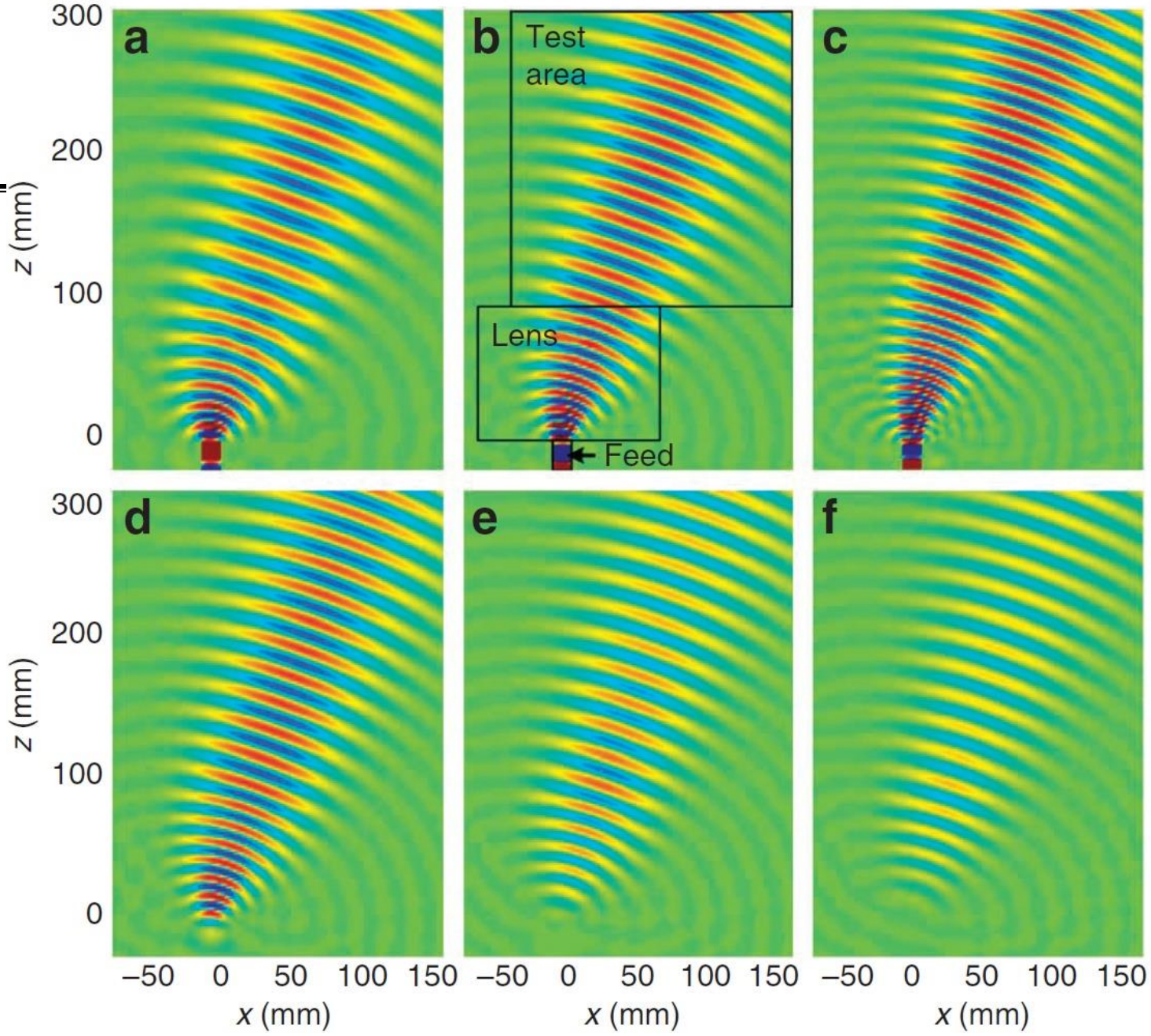




R = 70 mm, θ = 120°, d=108 mm, h=104 mm

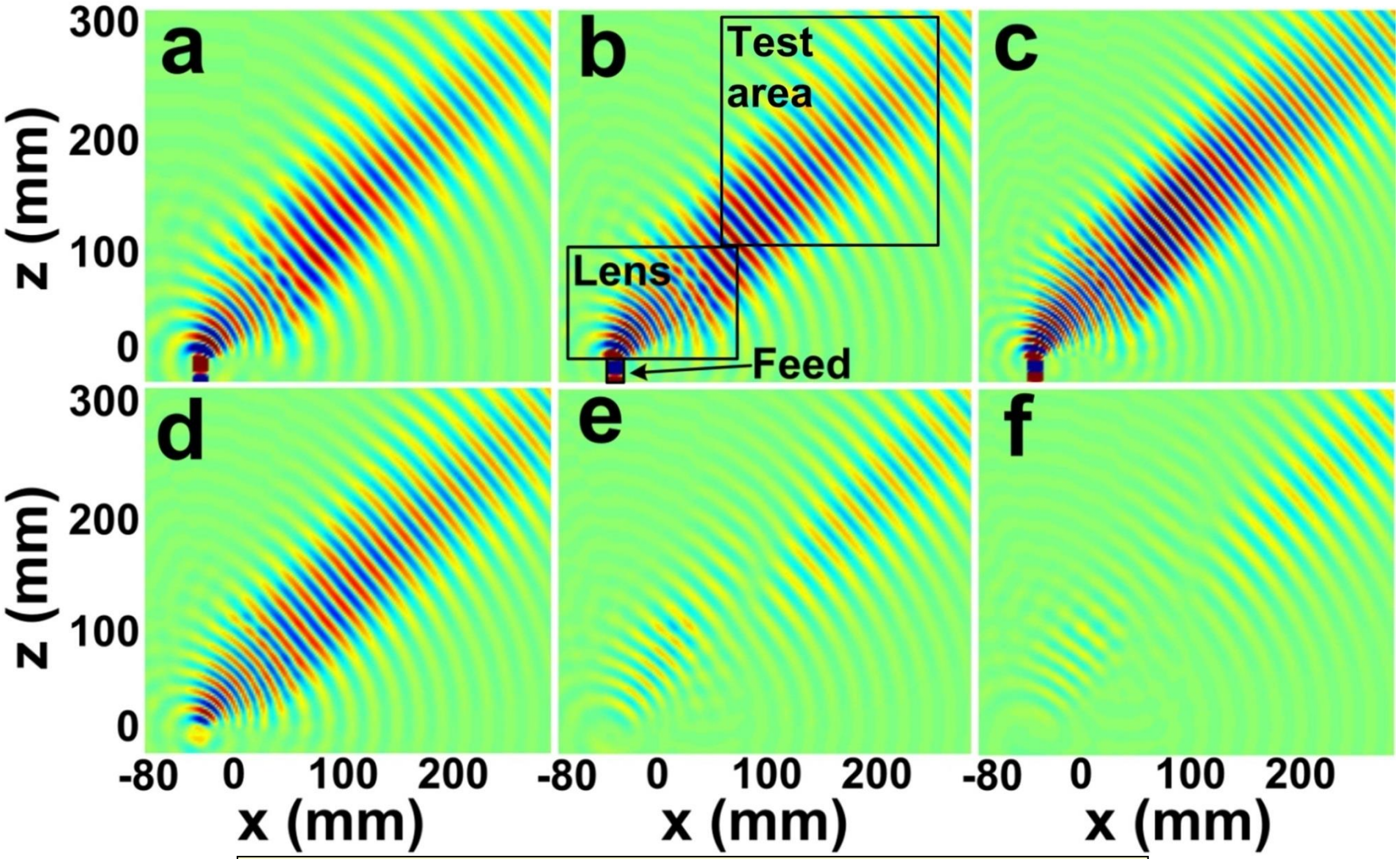


On the *y*=0 plane (containing the optical axis) at 12.5, 15, and 18 GHz



On *y*=10mm planes at 12.5, 15, and 18 GHz

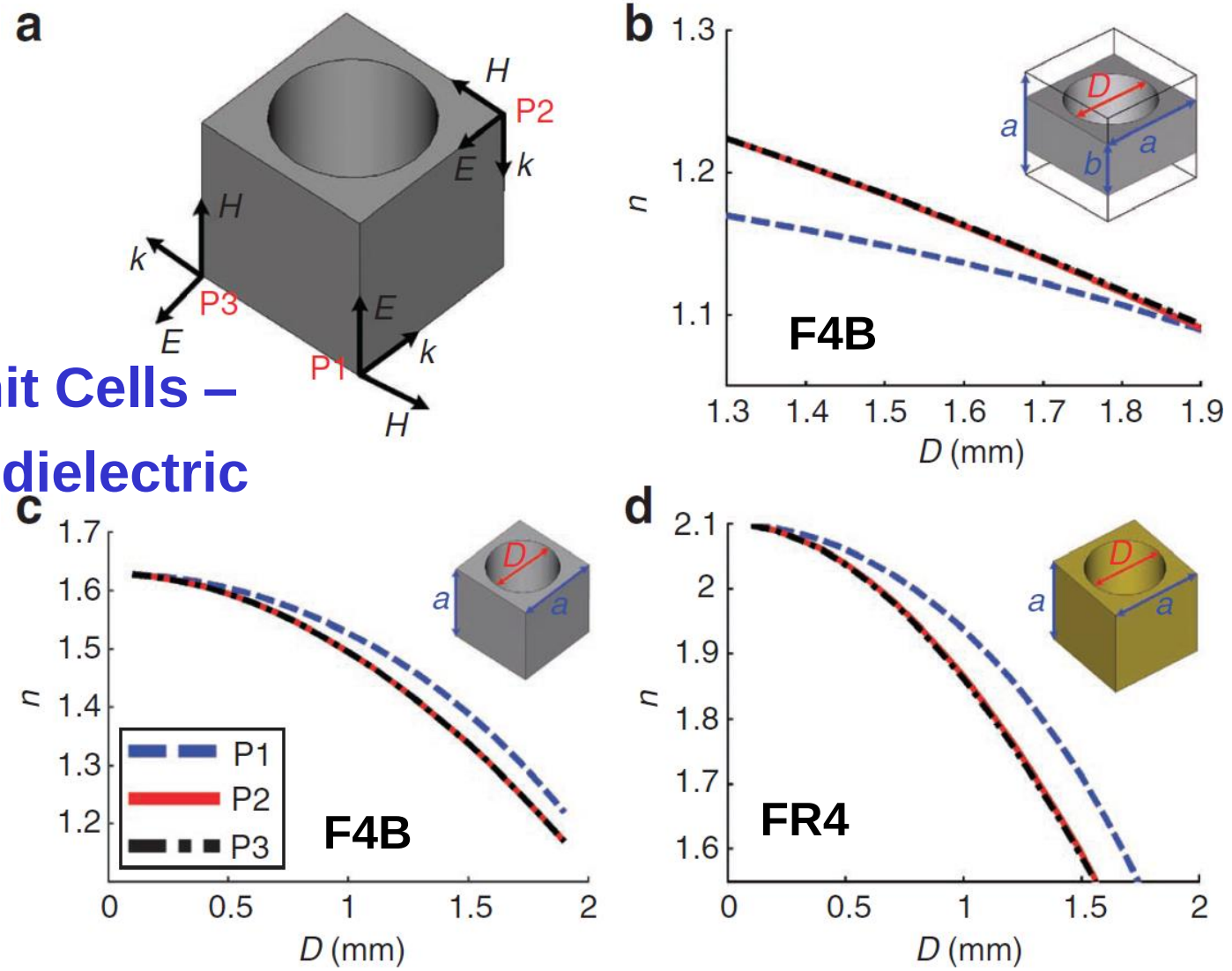
3D Transformation Optics Lens



On *y*=30mm planes at 12.5, 15, and 18 GHz

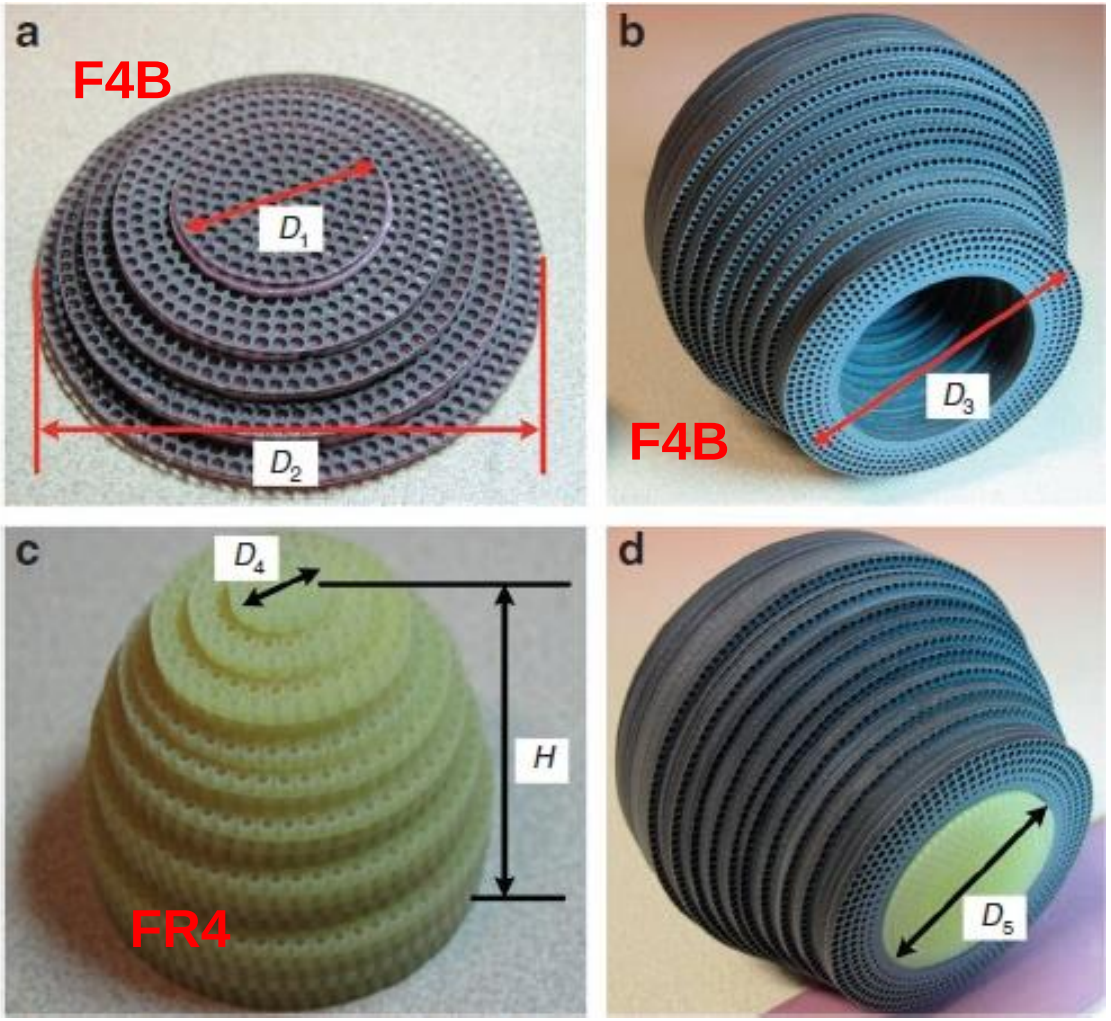
3D Transformation Optics Lens

- **Design of Unit Cells – Drilling-hole dielectric**



3D Transformation Optics Lens

◆Fabrication of Lens

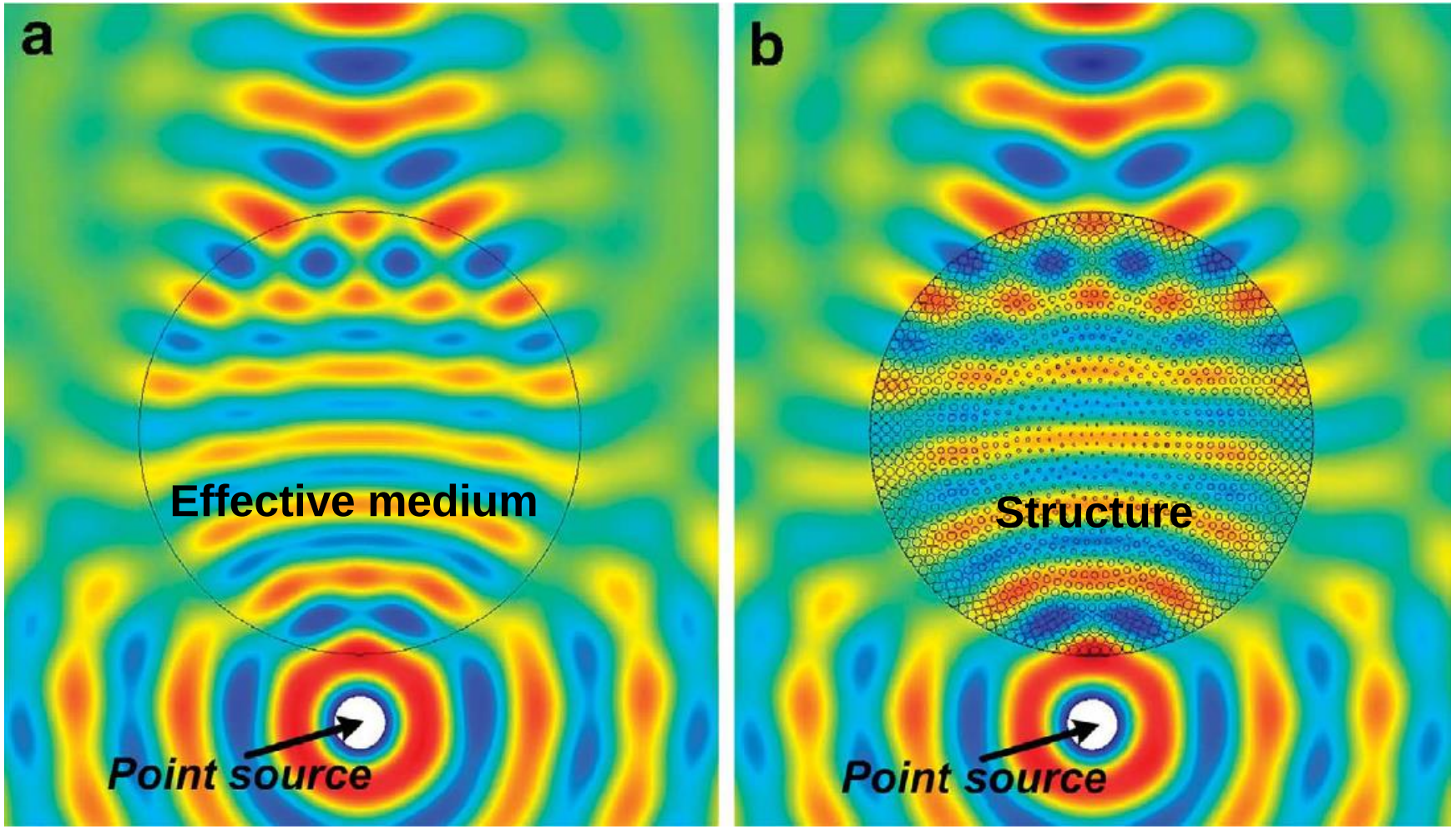


Height: 104 mm

Diameter: 108mm

Frequency: The Whole Ku Band

3D Transformation Optics Lens

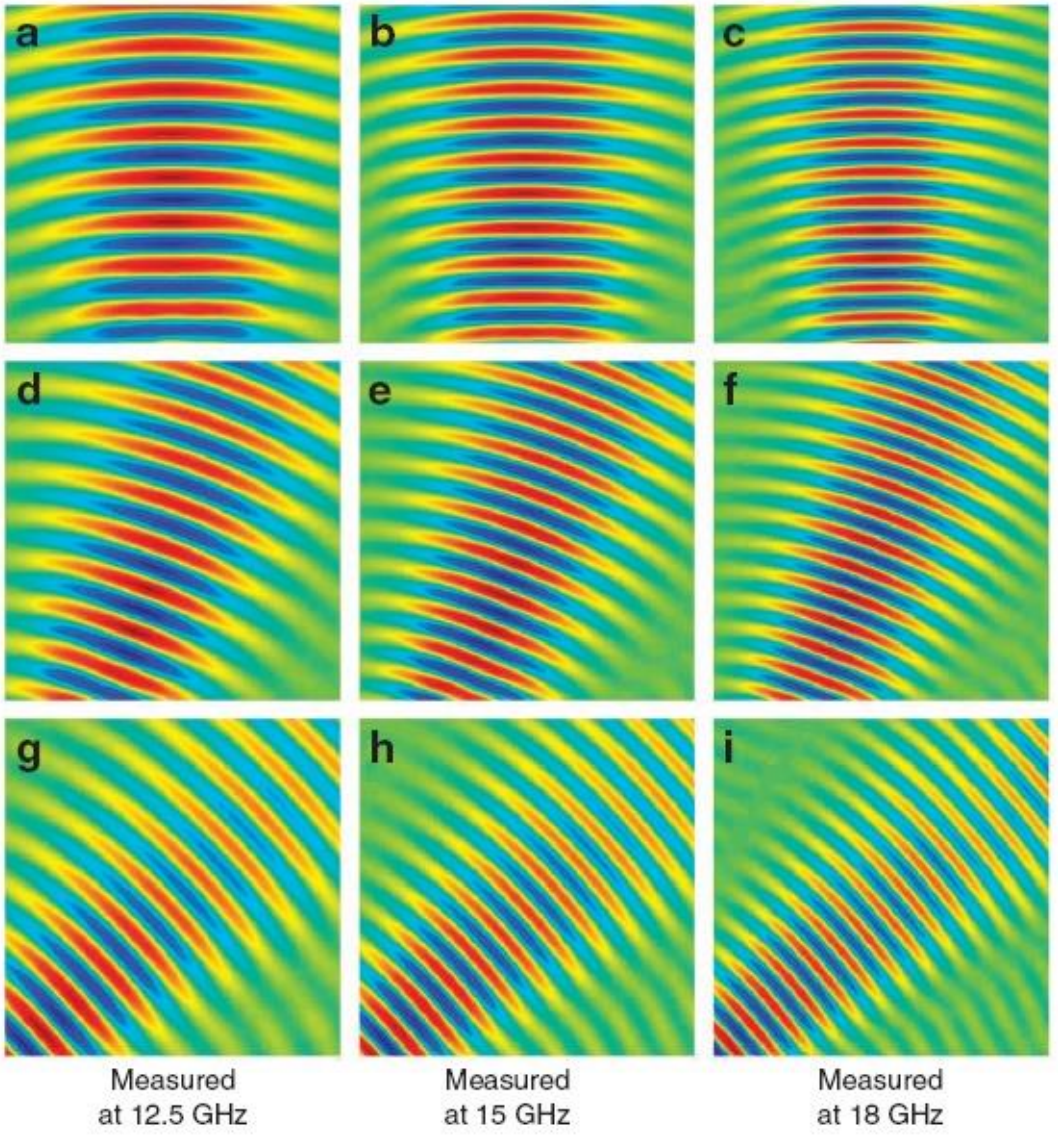


Effective medium vs actual structure

3D Transformation Optics Lens

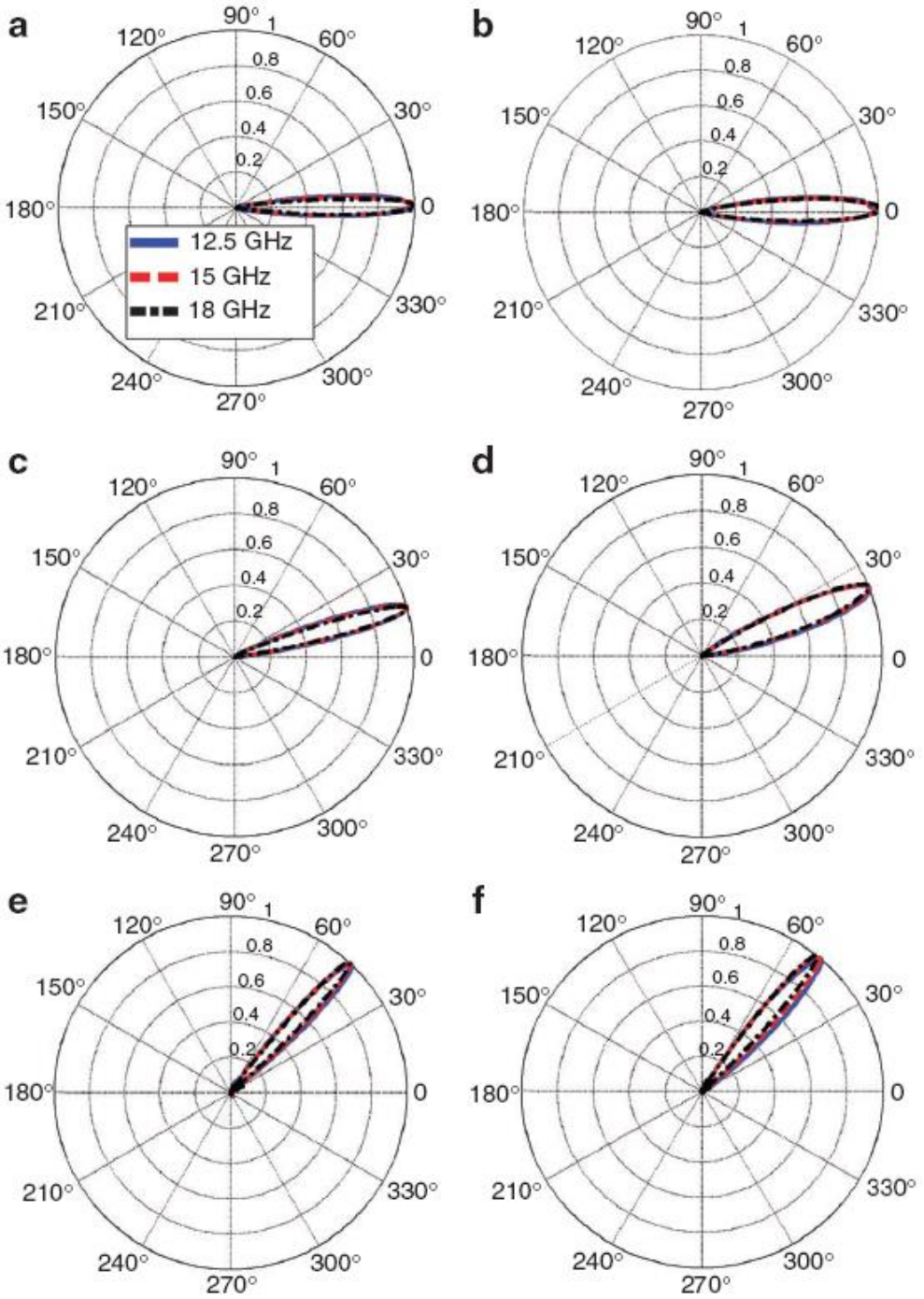
- **Measured Near Fields**

Measured near-field distributions when the feeding positions are different. A beam steering is observed.



◆ Measured Far Fields

Measured far-field radiation patterns when the feeding positions are different. A beam steering is observed.

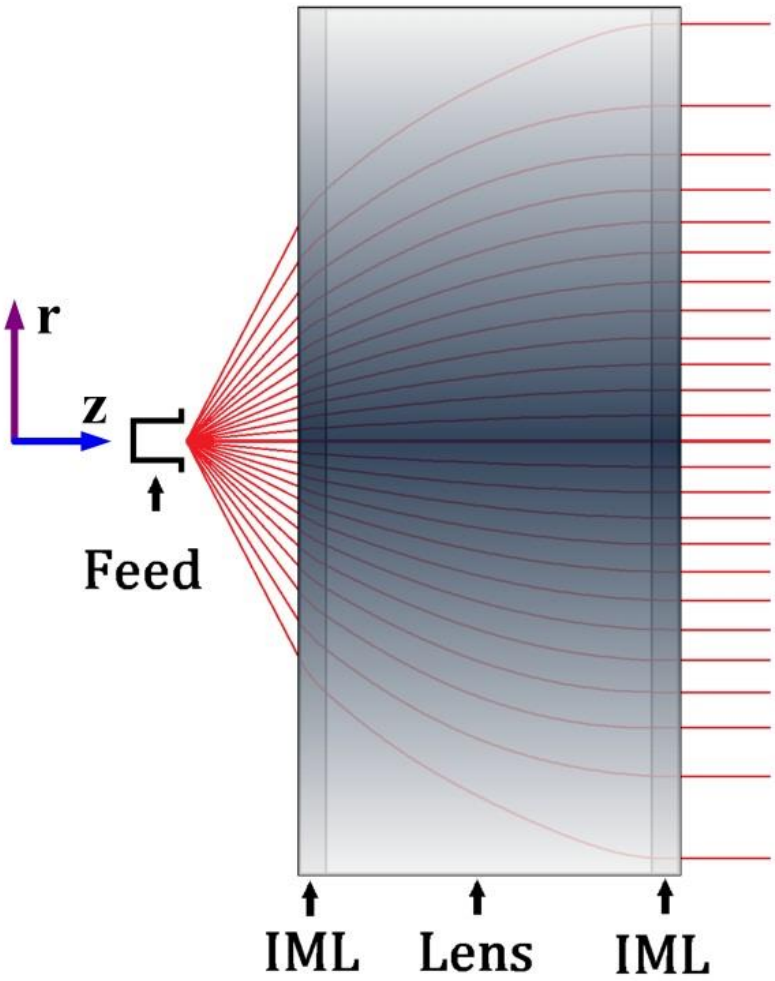


3D Transformation Optics Lens

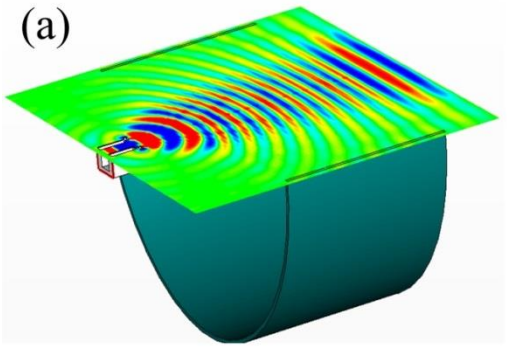
- **Good Features**

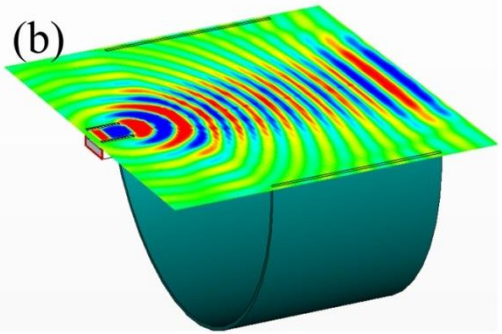
1) **High gain (22.7dBi);**
2) **Relatively low sidelobes;**
3) **Dual polarizations;**
4) **Large radiation angles (up to 50^{o});**
5) **Broad band (from 12 to 18 GHz).**

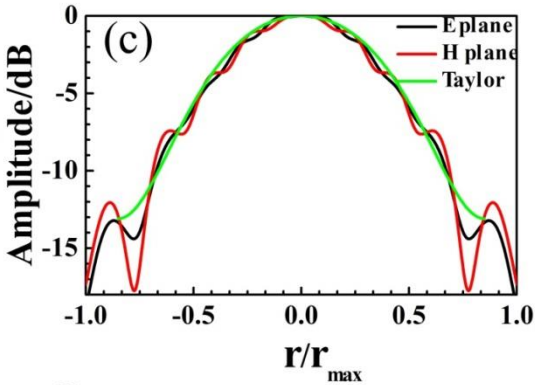
General 3D Metamaterial Lens

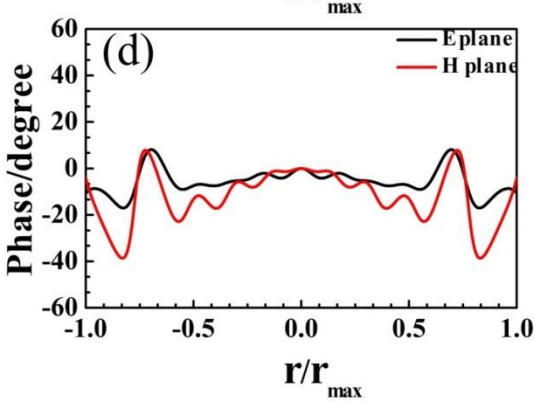


- Control both amplitude and phase distributions of the lens aperture



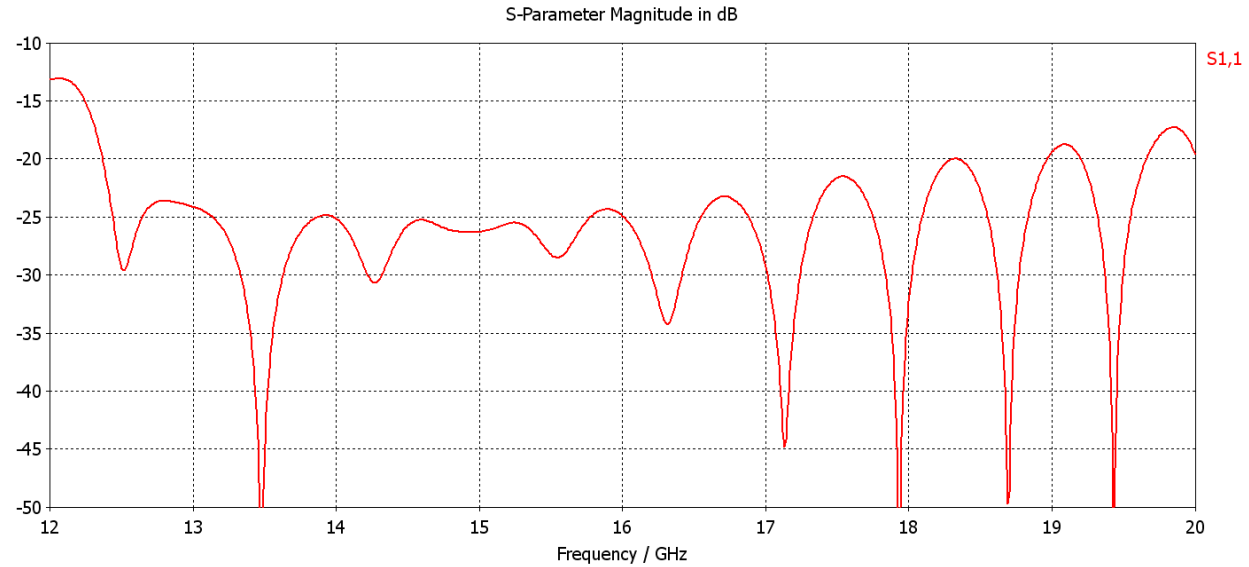




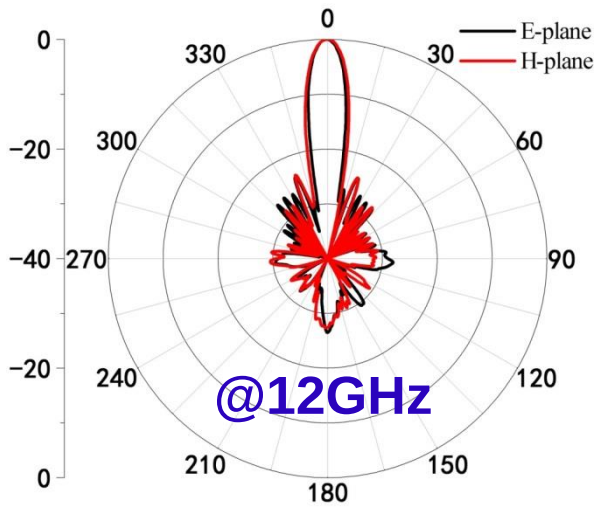


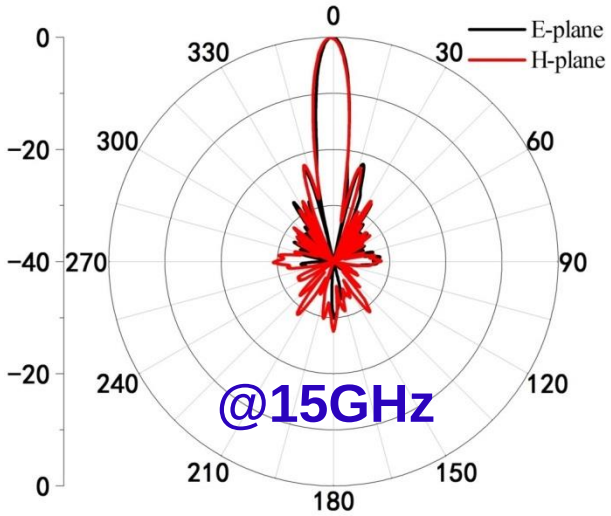
M. Q. Qi, T. J. Cui et al., IEEE Transactions on Antennas and propagation, Vol. 61, pp. 5792-5798, 2013

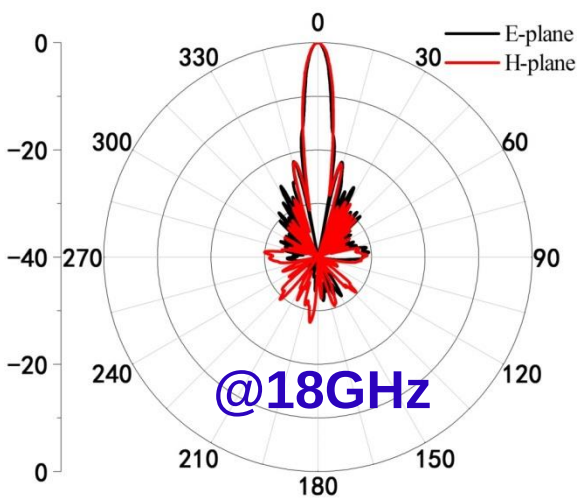
General 3D Metamaterial Lens



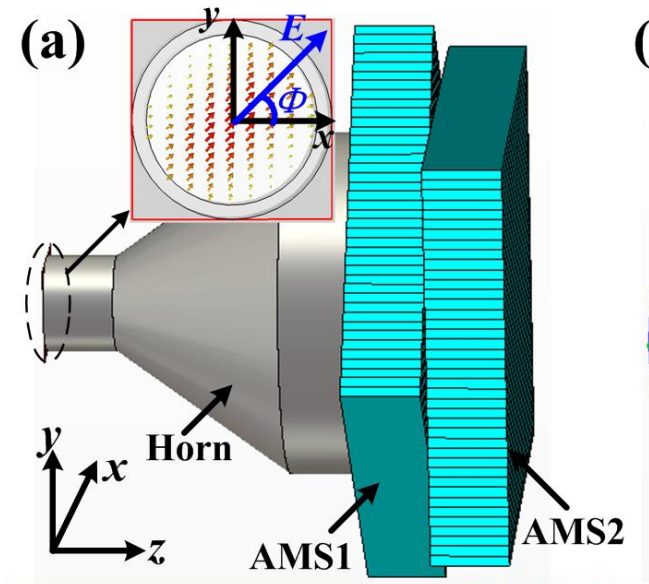
- ✓ Broadband
- ✓ Low sidelobe
- ✓ High efficiency

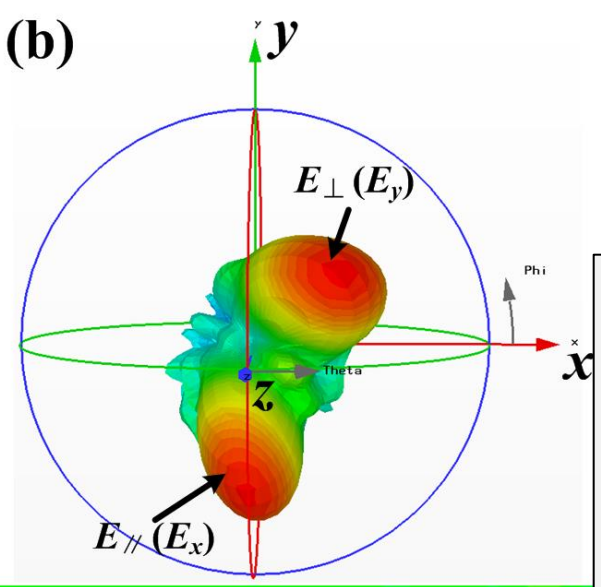






Anisotropic 3D GRIN Lens





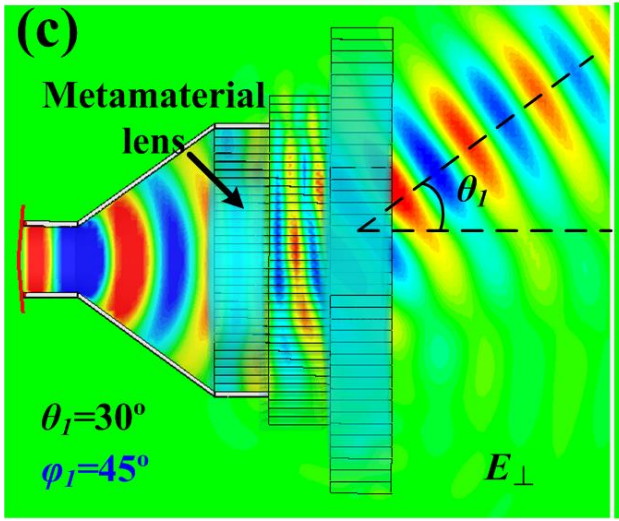
High-Gain Polarization Splitter

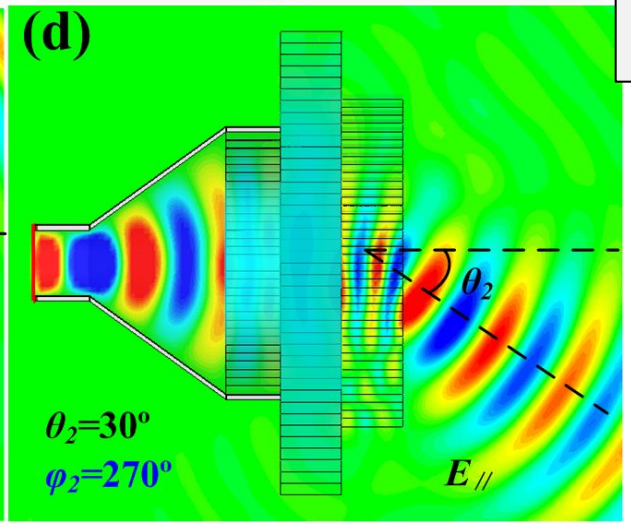
(a) 3D Model

(b) Radiation Pattern

(c) Vertical Polarization

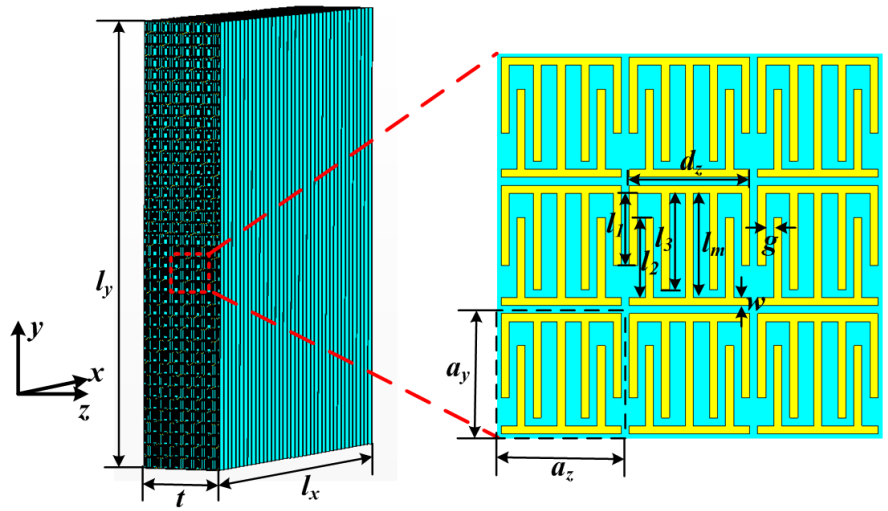
(d) Horizontal Polarization

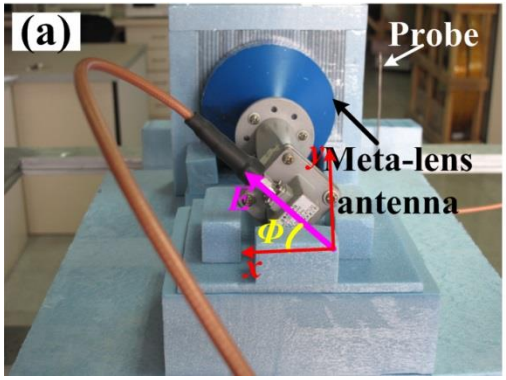


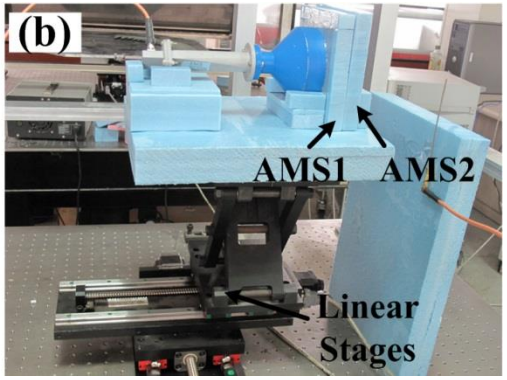


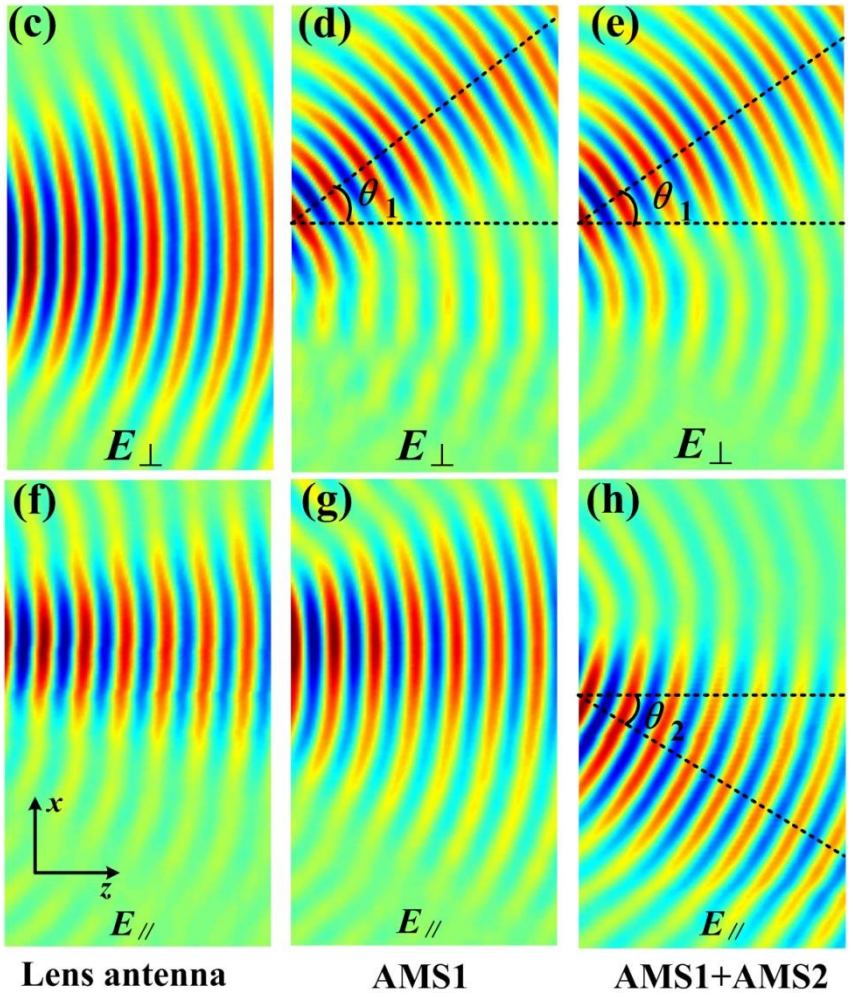
H. F. Ma, T. J. Cui, *et al.*, Scientific Reports, vol. 4, 6337, 2014

Anisotropic 3D GRIN Lens









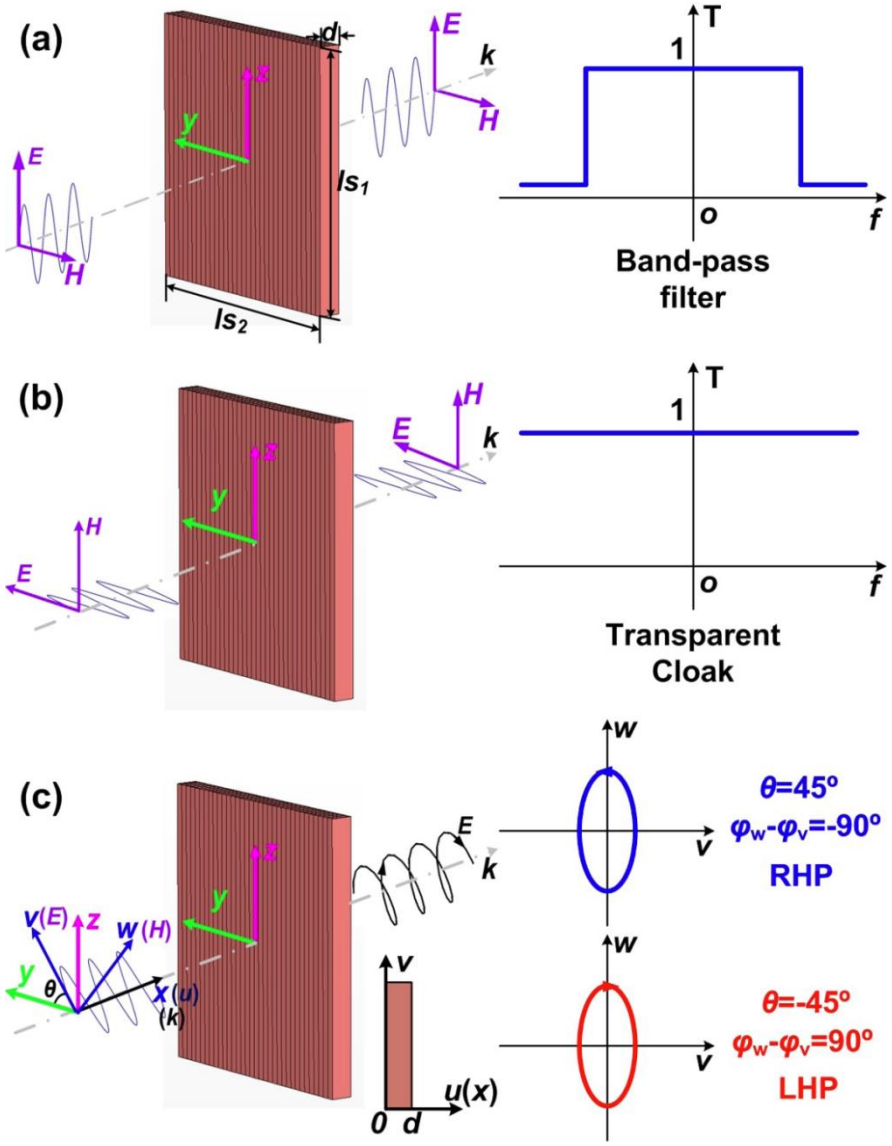
3D Multi-Functional Anisotropic Lens

(a) Bandpass Filter for the Z Polarization Incidence

(b) Transparent Slab for the Y Polarization Incidence

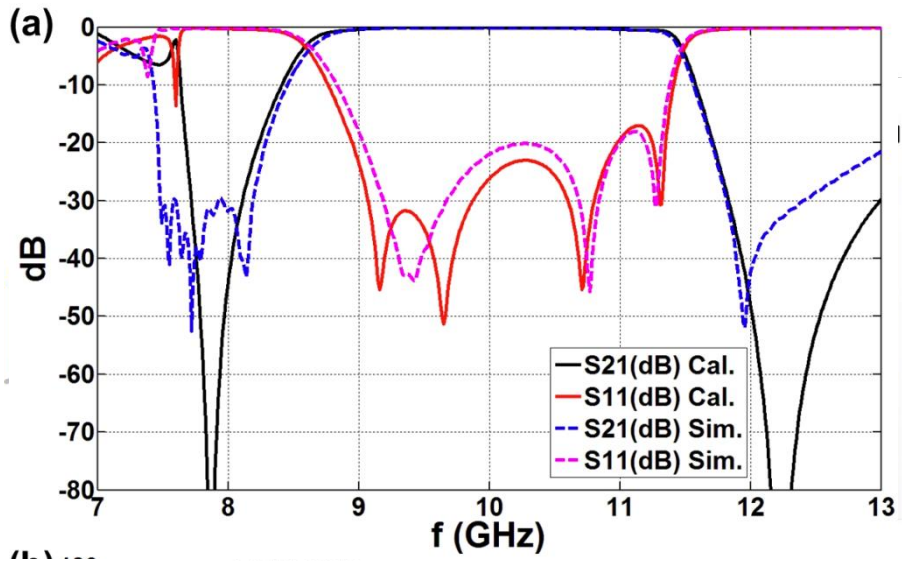
(c) Polarization Converter for v Polarization Incidence

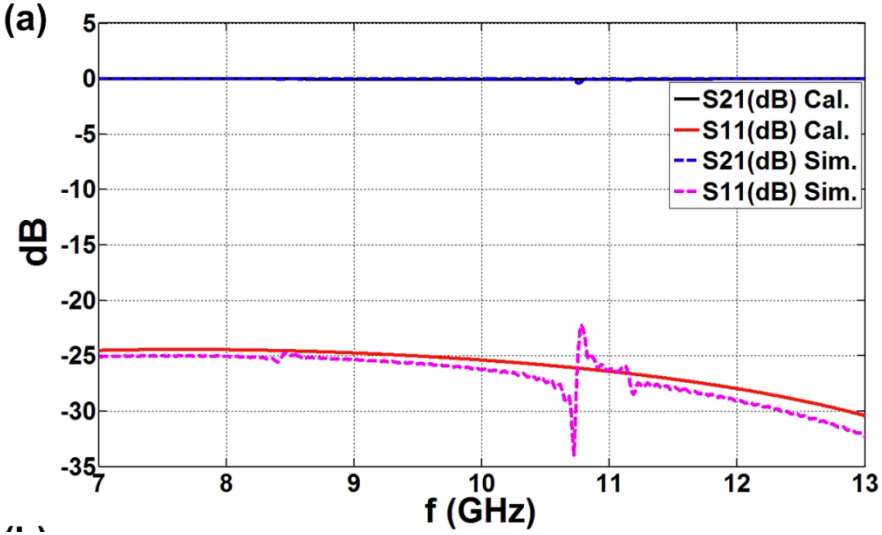
Special Antenna Radome

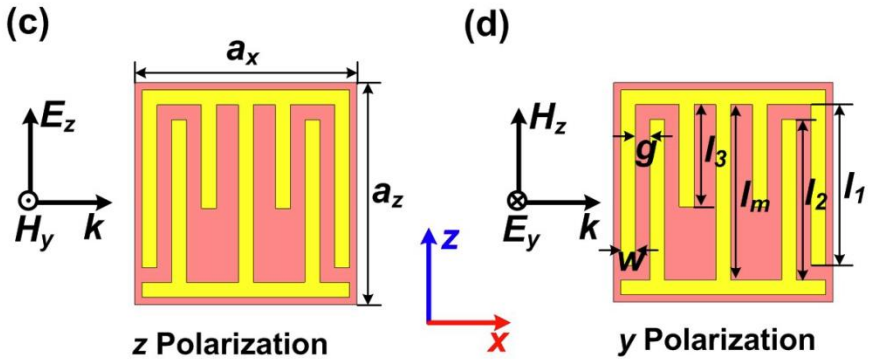


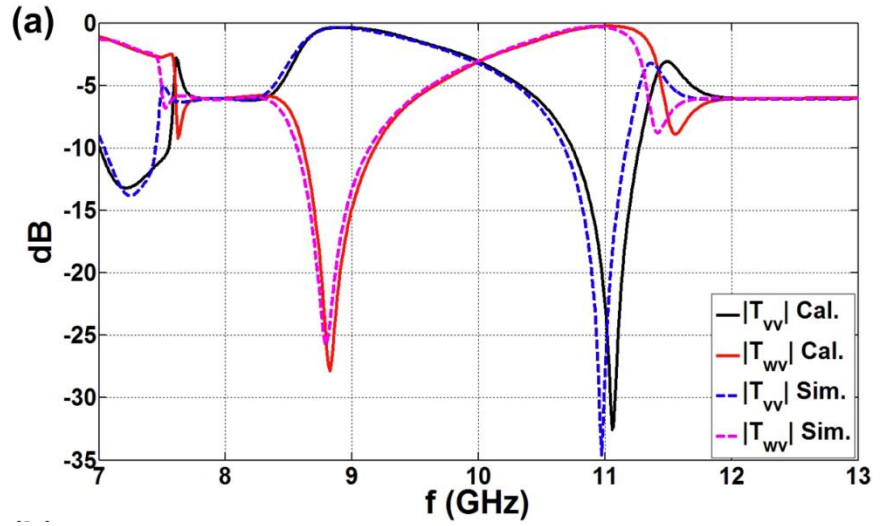
H. F. Ma, T. J. Cui, *et al.*, Applied Physics Letters, vol. 105, 081908, 2014

3D Multi-Functional Anisotropic Lens





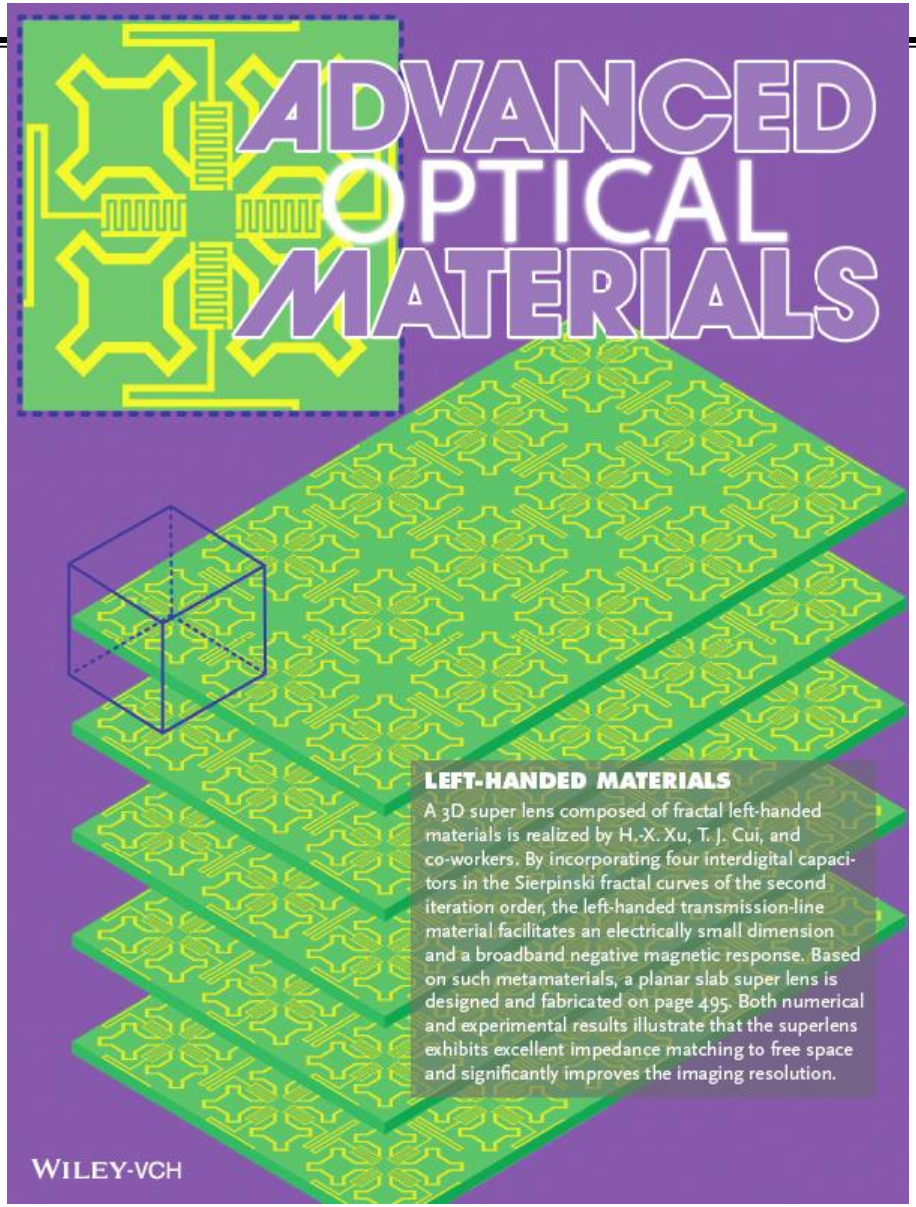




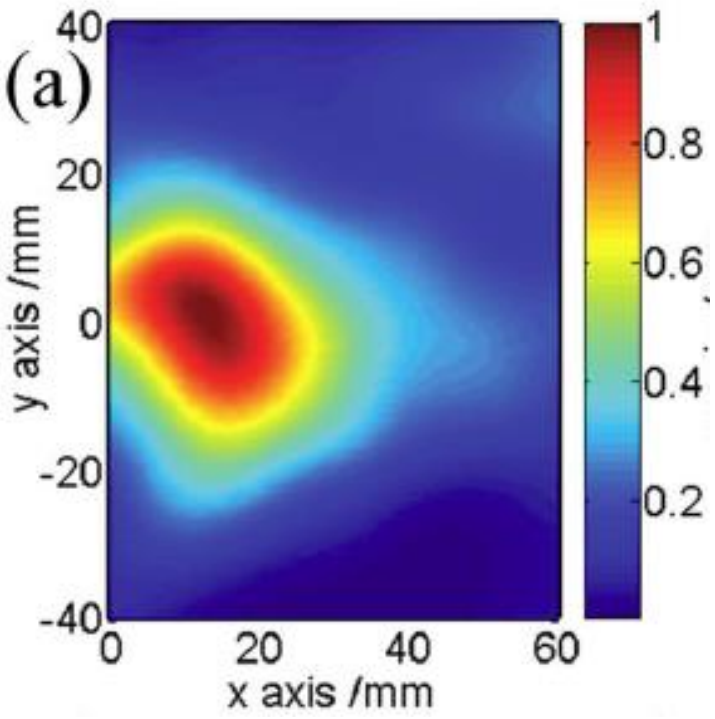
Other Applications

- **3D left-haned super lens;**
- **Metamaterial absorbers (Microwave absorber, THz absorber and tunable absorber);**
- **Metamaterial random surface.**

3D Left-handed Super Lens

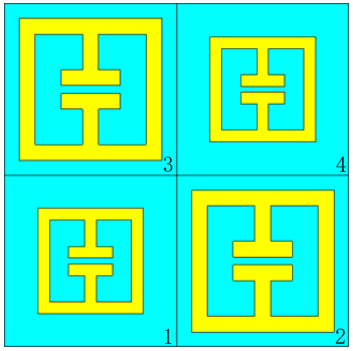


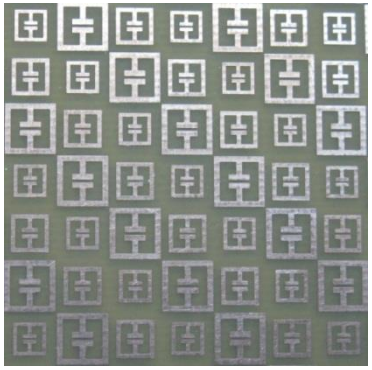
- 3D LHM Super Lens
- Fractal Particle
- Compact Size
- 0.45-Wavelength Spot

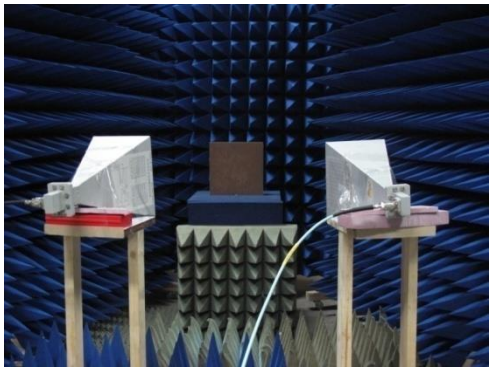


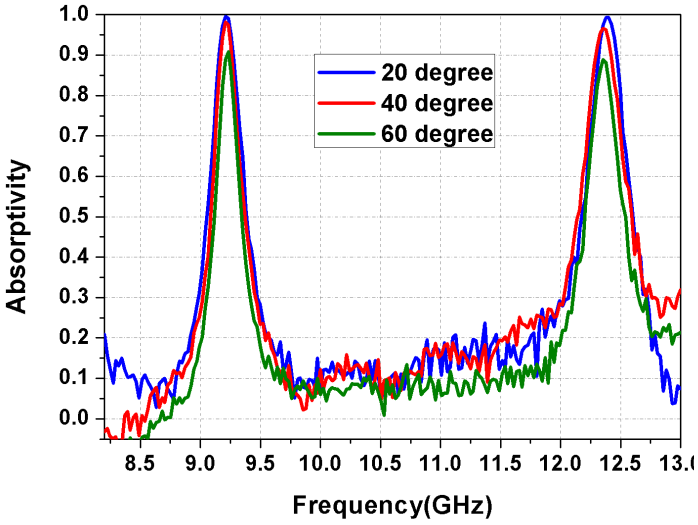
X. Xu, T. J. Cui, et al., Advanced Optical Materials, vol. 1, pp. 495-502, 2013

Dual-band Microwave Absorber

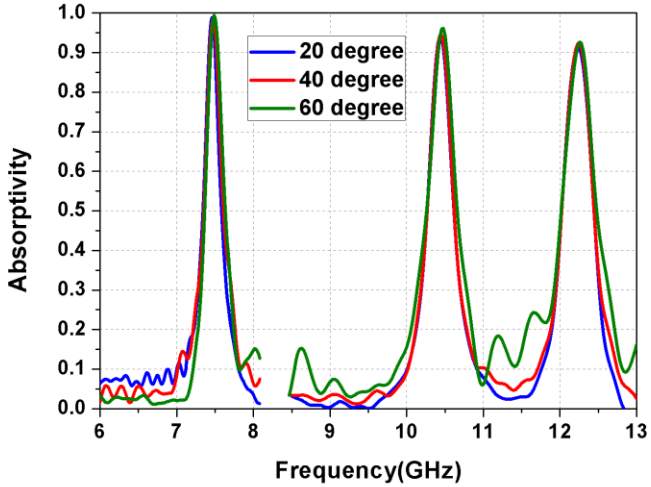






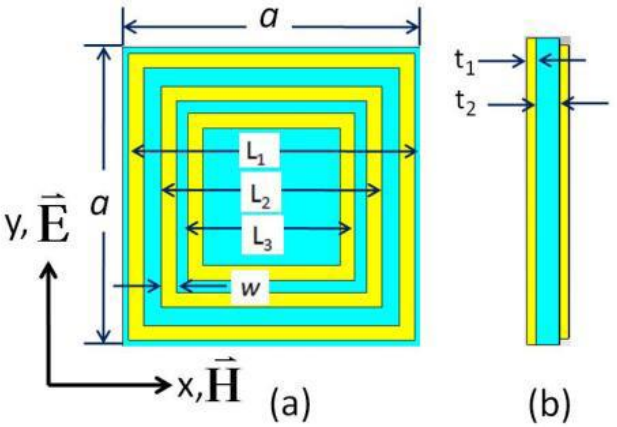


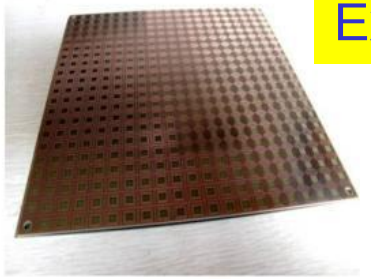
Very thin: 1mm
Large angles: 0-70 degrees
Polarization independent



H. Li, T. J. Cui, *et al*.
Journal of Applied Physics, vol. 110, 014909, 2011

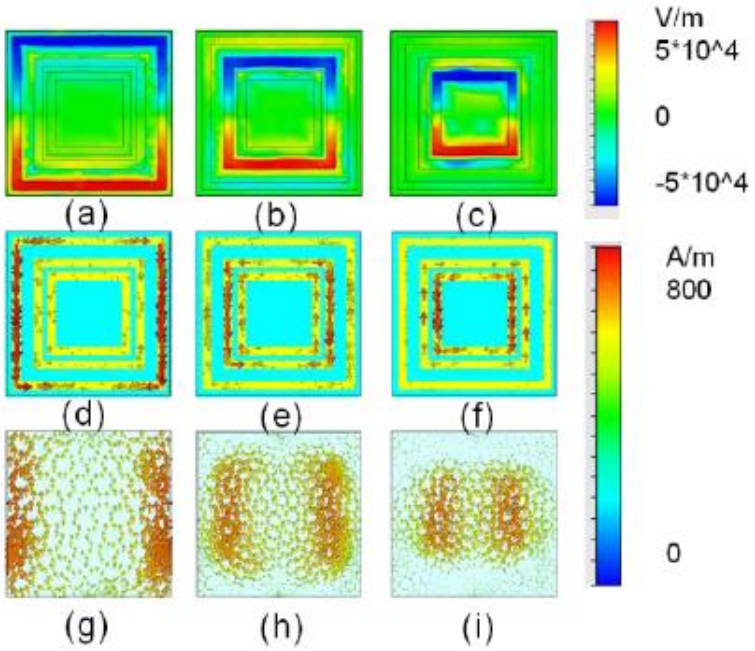
Tri-band Microwave Absorber

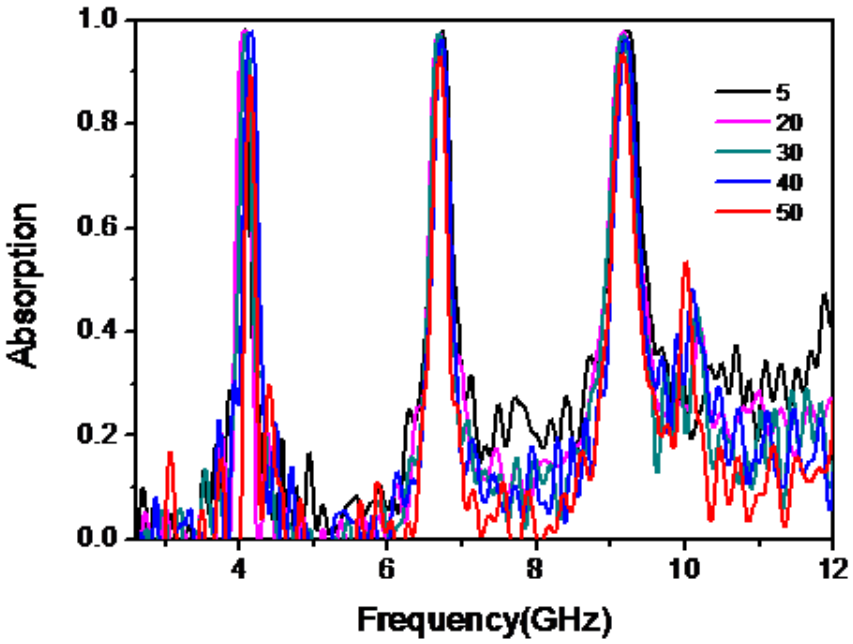




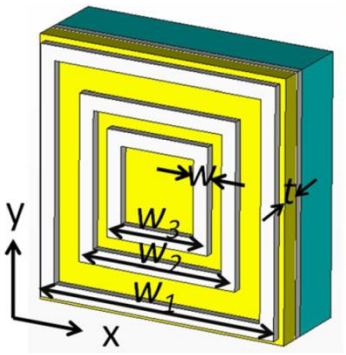
X. P. Shen, T. J. Cui, *et al*. Optics Express, vol. 19, 9401-9407, 2011

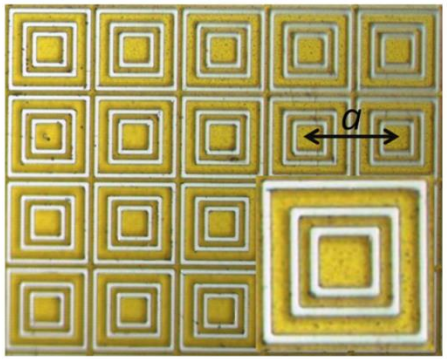
Very thin: 1mm
Large angles: 0-70 degrees
Polarization independent



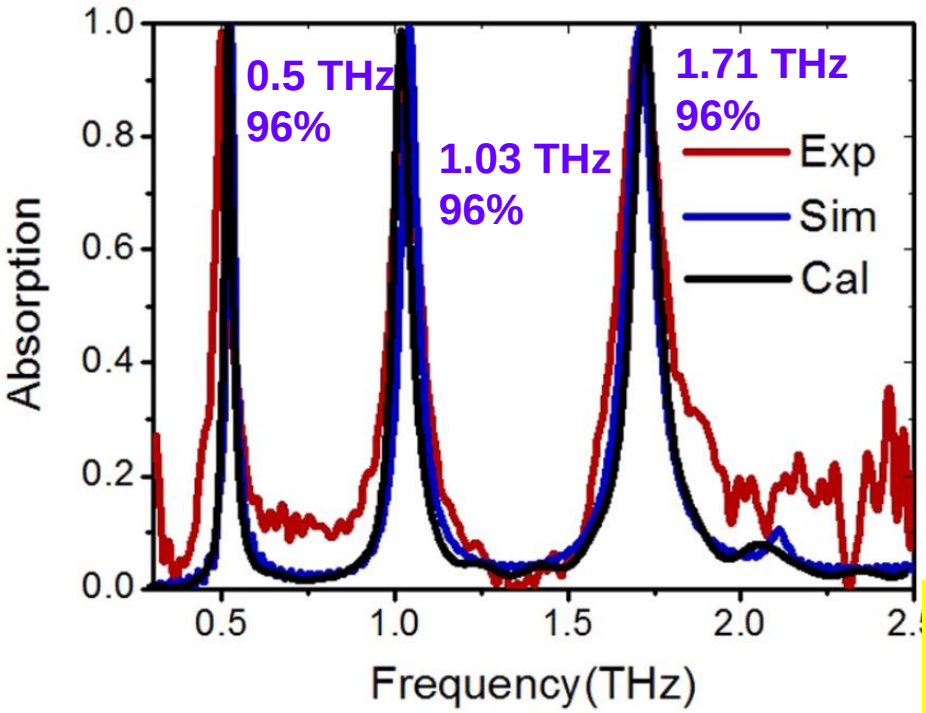


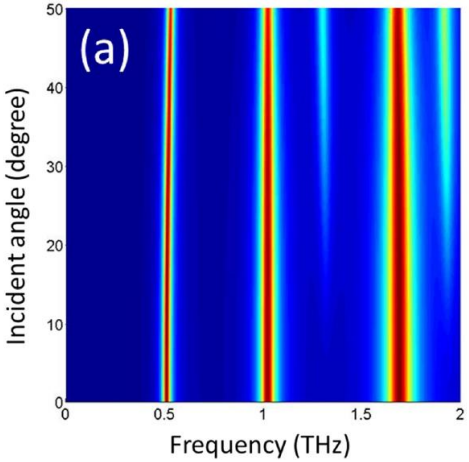
Tri-band Terahertz Absorber





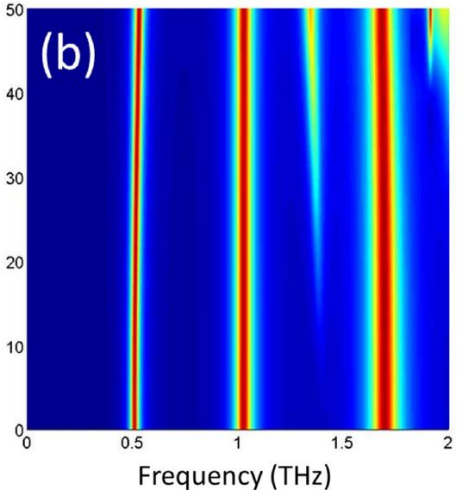
$w_1 = 84\ \mu m$, $w_2 = 56\ \mu m$, and $w_3 = 36\ \mu m$





TE

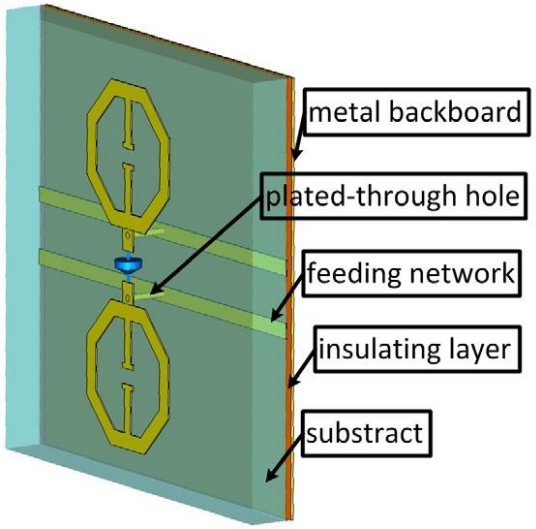
TM

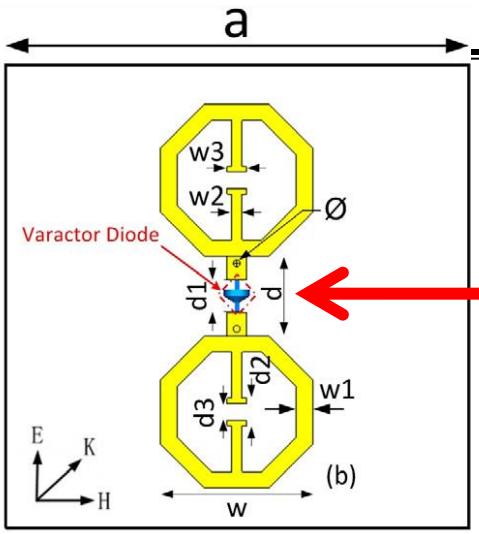


Collaborated with Prof. Weili Zhang at Tianjin University

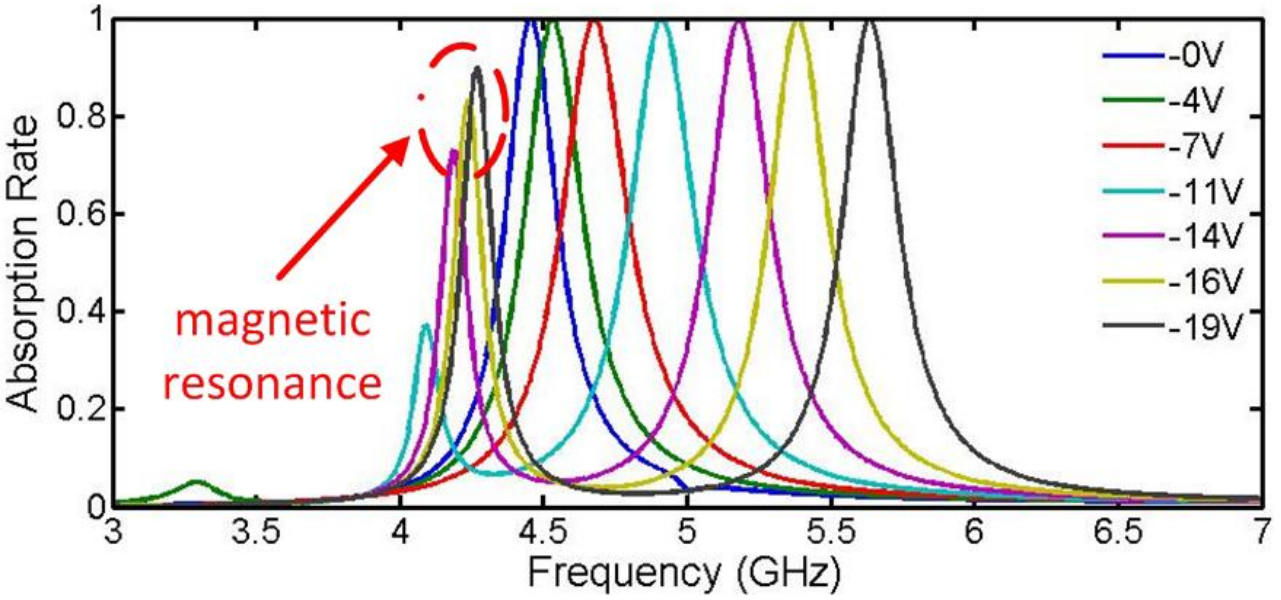
X. Shen, T. J. Cui, *et al*. Applied Physics Letters, vol. 101, 154102, 2012

Tunable Absorber



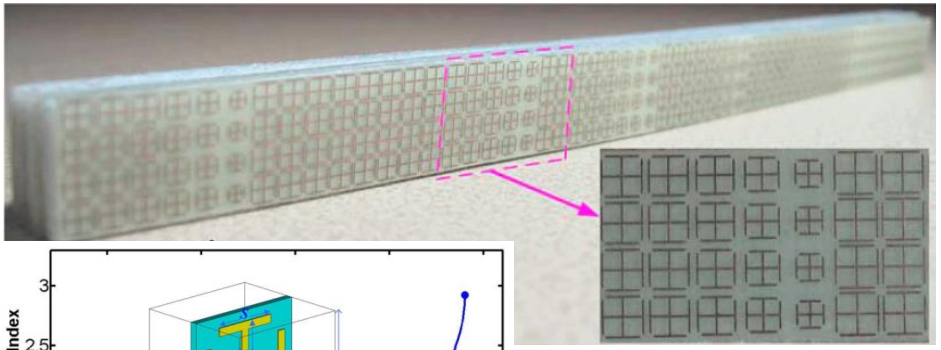


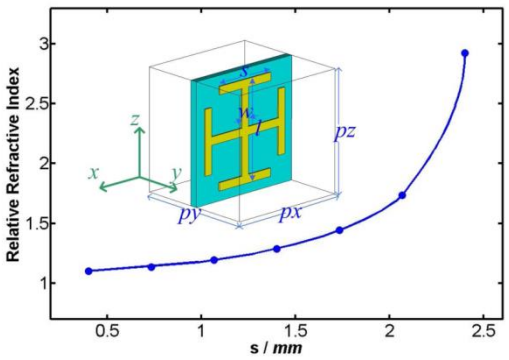
Variable capacitance diode

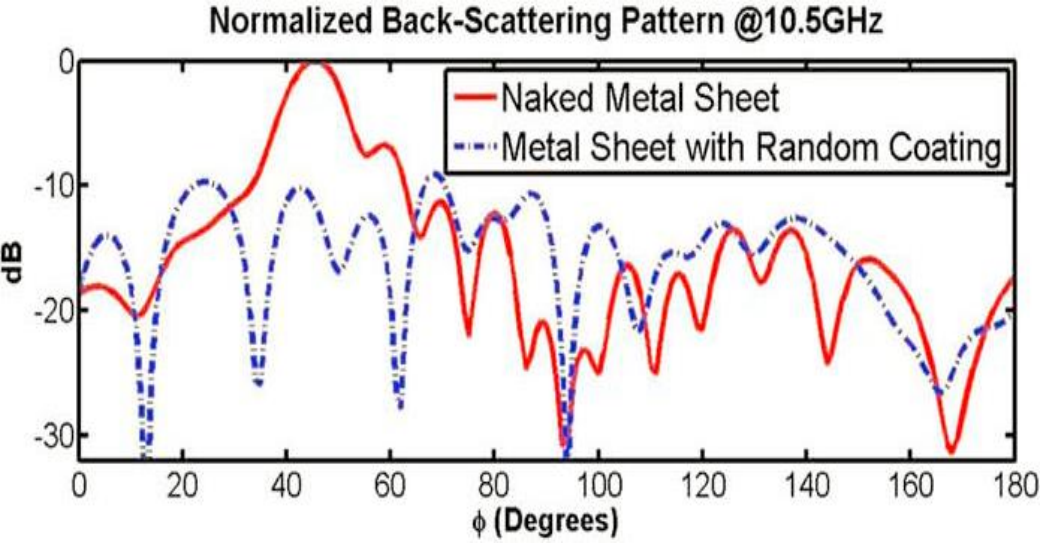


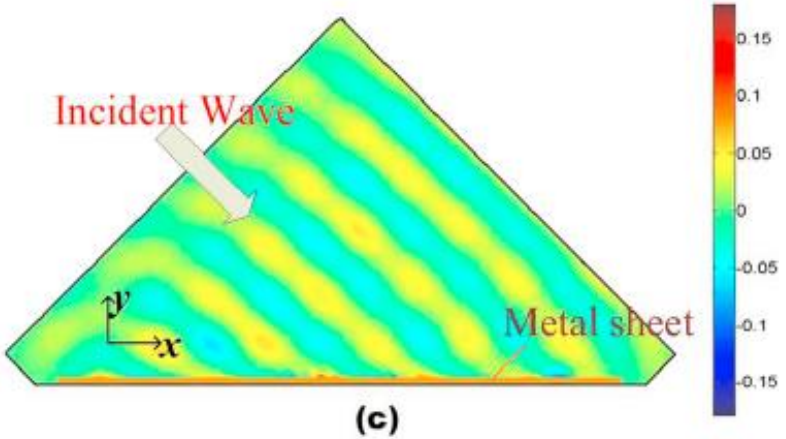
J. Zhao, T. J. Cui, *et al*. New Journal of Physics, vol. 15, 043049, 2013

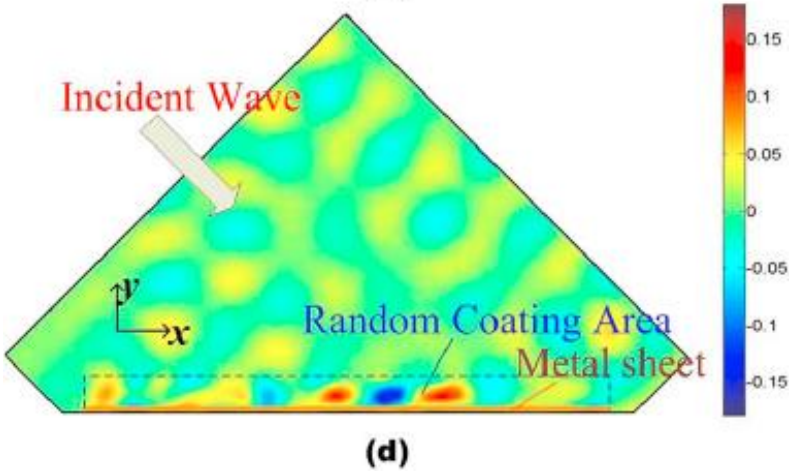
Diffuse Reflections by Random surface











X. M. Yang, H. F. Ma, T. J. Cui, Optics Letters, vol. 35, 808, 2010.

Summary

- Small metamaterial antennas are good choices for wireless communications.
- ZIM and AZIM are attractive for new metamaterial antennas.
- GRIN slab lens can be designed as high-gain antennas.
- Transformation optics lens is a representative of new-concept antennas, which can be used as a small phase array.
- Controlling both amplitude and phase of aperture makes metamaterials more attractive.
- Absorbers and random surface have potential application for invisibility.